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Quaternary stratigraphy and surficial geology of the Sand River area 73L

L.D. Andriashek and
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Addendum

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Cover: Aerial view of rimmed-ridged moraine partly buried by organic sediment, southwest corner of Department of National Defense Air Weapons Testing Range, Township 67, Range 7, West 4 Meridian.

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Abstract

This document describes the Quaternary stratigraphy, surficial geology, and Quaternary history of the area covered by the Sand River map sheet NTS 73L, east-central Alberta.

Eight glacial and nonglacial formations are defined for the Quaternary sequence in the Sand River area. The thick drift cover, combined with a paucity of exposures, necessitates reliance on test hole data for the differentiation and correlation of these units.

The stratigraphy of the upper 50 m is defined primarily from sediment grain size and carbonate content, and from very-coarse-sand composition data derived from dry auger samples at 1 m intervals. Rotary drill samples and electric-log responses are essential to define the deeper stratigraphy.

The relative abundance of four rock groups (igneous and metamorphic rock, quartz, carbonates and local bedrock) within the 1- to 2-mm sand fraction are the most useful criteria in differentiating the tills. The standardization of electric-log responses with the analytical values enables correlations of the units beyond areas where samples were collected. Textural and lithologic variations allow the division of some formations into units or members.

The formations are named and type sections designated. The Empress Formation is the oldest, and is divided into three units on the basis of lithology: unit 1, preglacial sand and gravel; unit 2, silt and clay; and unit 3, glacial sand and gravel. The Bronson Lake Formation overlies the Empress Formation. It consists of clayey till and clay deposited by the first glacier in the area, the Cherry Grove Glacier. Glaciofluvial sand and gravel of the Muriel Lake Formation were deposited on top of the Bronson Lake Formation, both during the retreat of the Cherry Grove Glacier and during the advance of the Fort Kent Glacier. Till of the Bonnyville Formation overlies the Muriel Lake Formation. It was deposited by the Fort Kent Glacier, and is characterized by a relative abundance of quartz and a paucity of carbonate in the silt-clay and very-coarse-sand fractions.

Glaciolacustrine silt and clay of the Ethel Lake Formation were deposited in proglacial lakes during the advance of the Ardmore Glacier. Till of the Marie Creek Formation was deposited during later stages of that advance. The till is characterized by a relative abundance of carbonate rocks, mainly dolostone, in the silt-clay and very-coarse-sand fractions.

Glaciofluvial sand of the Sand River Formation was deposited during the retreat of the Ardmore Glacier as well as during the advance phase of the subsequent Cold Lake Glacier.

The Grand Centre Formation consists of till and glacially displaced sediment deposited by the last glacier in the area, the Cold Lake Glacier. The till is characterized by an abundance of igneous and metamorphic rock fragments in the very-coarse-sand fraction. Four members, defined mainly by grain size, are recognized within the formation.

The presence of oxidized profiles on the surfaces of the till formations suggests that lengthy periods of weathering followed each major glacial episode.

The surficial geology is mapped according to a classification based on genesis, composition, and morphology and relief, with each category indicated on the map by a symbol. The genetic categories, the first level of subdivision, are designated organic, colluvium, fluvial, eolian, lacustrine, moraine, and bedrock. The composition categories indicate the dominant grain size of the sediment (silt and clay for example), and for some of the moraine units, the presence of significant quantities of recognizable bedrock inclusions.

A combination of letters and numbers is used to designate each map unit, for example ctMSDh2. The lowercase letters (where present) preceding the capitals indicate the composition of the unit. The first uppercase letter indicates the genetic class. The following uppercase letter(s) indicate the genetic modifier and provide additional information about the genetic unit. The lowercase letters following these indicate the morphology type and the amount of local relief. The absence of the compositional, genetic, or morphologic modifier for a particular unit indicates that the data are insufficient to determine that property.

The Sand River area includes some types of glaciotectonic landforms not previously described. Three broad types recognized in the study area are the hill-hole pair, hills with a fault-bounded depression, and rubble terrain. Hill-hole pairs form a major portion of the thrust moraine, and consist of a hill and an associated up-glacier depression that is commonly water-filled to form a lake.

Hills with fault-bounded depressions consist of a hill-hole pair in which the up-glacier depression is bounded on at least one side by a linear margin believed to represent the trace of a tear fault created during the glacial excavation of the sediment. Rubble terrain consists of a group or series of hills composed of a mixture of syngenetic till and distinct blocks of preexisting sediment. Typically the hills decrease in size down-glacier from the source depression.

The Late Wisconsinan history began with the advance of the Cold Lake Glacier over the area. This glacier advanced in the form of three independent lobes, each of which flowed beyond the limits of the area. The southwestward-flowing lobe, the Primrose Lobe, deposited the Hilda Lake and Reita Lake members of the Grand Centre Formation in the eastern half of the area. The southward-flowing lobe, the Seibert Lobe, deposited the Kehiwin Lake Member of the Grand Centre Formation in the western half of the area. The youngest lobe, the Lac La Biche Lobe, flowed southeastward and deposited the Vilna Member of the Grand Centre Formation over part of the western half of the area.

During the late stage of the Cold Lake Glaciation the Sand River developed as an ice-walled channel along the north-south trending margin of the Primrose and Seibert lobes. The Sand River first flowed along the north-south portion of the present Sand River channel into the Truman and Minnie Lake segments, and later into the Kehiwin Channel. Fluctuations in the Primrose Lobe margin resulted in the eventual infilling and abandonment of the Truman and Minnie Lake segments, and the formation of the Moose Lake River and Moose Lake. Later, drainage within the southern few kilometres of the Sand River was diverted southeastward into the Moose Lake River. The present-day Beaver River channel developed west of the Sand River at this time, subsequent to the stagnation of the Seibert Lobe. East of the Sand River the subsequent stagnation of the Primrose Lobe resulted in a northward shift of the active ice margin to a position north of the present-day Beaver River channel. This allowed the development of the eastern segment of the Beaver River and the subsequent abandonment of the Moose Lake River–Kehiwin Channel drainageway. A *minor glacial readvance southwestward out of Cold Lake temporarily blocked the eastern half of the Beaver River and likely resulted in a short-lived rejuvenation of the Kehiwin Channel drainageway. Following this, drainage along the eastern channel of the Beaver River was reestablished and the present-day drainage pattern developed.*

Introduction

The recent expansion of the heavy oil industry in east-central Alberta has placed demands for new and varied sources of geologic construction material, as well as an understanding of the geotechnical and hydrogeologic properties of the overburden. In anticipation of this need for surface and subsurface information, the Alberta Geological Survey initiated a study in 1976 of the Pleistocene and Holocene deposits that overlie the heavy oil sand in the Sand River map area (National Topographic System map reference number NTS 73L).

The main objective of the project was to define the Pleistocene stratigraphic units according to lithologic properties, thickness, distribution, and genesis. To accomplish this, a dry-auger drill program and a Quaternary-geology mapping program were initiated. The information derived was supplemented by existing information from water-well drillers, oil companies and previous workers (Gold 1978; Yoon and Vander Pluym 1974). Grain size and petrography of the very-coarse-sand fraction proved to be the most effective for differentiating units containing till. Using these compositional properties, along with the geophysical logs, the units were correlated throughout the map area.

Names have been assigned to the stratigraphic units, modelled after the format defined by the Canadian Society of Petroleum Geologists Lexicon Committee (Alberta Society of Petroleum Geologists 1960) for naming geologic units. An attempt has been made to correlate these units with those previously defined in Saskatchewan (Christiansen 1968).

The results of this study suggest that at least four major glaciations have occurred within the Sand River map area. Datable material was not found within any of the units; consequently the dates of these glaciations are unknown.

Location and geography of the study area

The Sand River map area is located in east-central Alberta (latitude 54 to 55°, longitude 110 to 112°); the Alberta-Saskatchewan boundary forms the eastern margin (figure 1). The study area encompasses about 14 000 km^2 and includes Tp 58-69 and R 1-13, W 4 Mer. Alberta highways 28, 28A, and 36 connect the major communities, the largest being the town of Bonnyville in the central part of the map area, Lac La Biche in the northwest, and Grand Centre and Cold Lake in the northeast.

Roads are generally good in the agricultural central and western parts of the map area, but poor or nonexistent in the north. About 2300 km^2 in Tp 67-69, R 1-9, in the northeastern part of the map area, are used by the Department of National Defense for an air weapons testing range and are inaccessible to the general public. Mapping within this area was done by helicopter.

Physiography of the study area

The Sand River map area lies within the Eastern Alberta Plains and the Mostoos Hills Upland regional physiographic units (Atlas of Alberta 1969). The northeast part of the map area lies in the Mostoos Hills Upland at an elevation above 600 m; the western and southern parts of the map area lie in the Eastern Alberta Plains at an elevation below 600 m.

Most of the map area is characterized by glacial terrain ranging from flat to hummocky, high-relief topography (Fenton and Andriashek 1983, in pocket). The area includes many lakes, the largest of which are Cold Lake in the east, Muriel Lake in the south, Pinehurst, Seibert, Wolf, Touchwood and Spencer lakes in the central part, and Lac La Biche and Beaver Lake in the northwest (figure 2). Many of the lakes have clear water and sandy beaches, which make the area popular for recreation.

The major rivers are the Beaver River and the Sand River. The Beaver River, the larger of the two, flows eastward from Beaver Lake and is part of the Churchill River drainage system. The Sand River flows south from its headwaters north of the map area and joins the Beaver River in the central part of the study area.

For the convenience of geologic discussions, the two major physiographic units have been subdivided on the basis of relief, elevation, and morphology (figure 2). The lowest of the physiographic units is the Beaver Lowlands in the eastern part of the map area at an elevation generally below 580 m. The unit is a flat to gently rolling till plain. The Beaver River flows eastward through the area, and in places fluvial or lacustrine plains occur next to the river.

The northern margin of the Beaver Lowlands is bounded by the Medley and Marguerite uplands (figure 2). The uplands range in elevation from about 580 m to as high as 730 m in the northern part of the map area. The Medley Upland is a low-relief to high-relief rolling and glacially streamlined terrain whereas the Marguerite Upland is characterized by a hum-

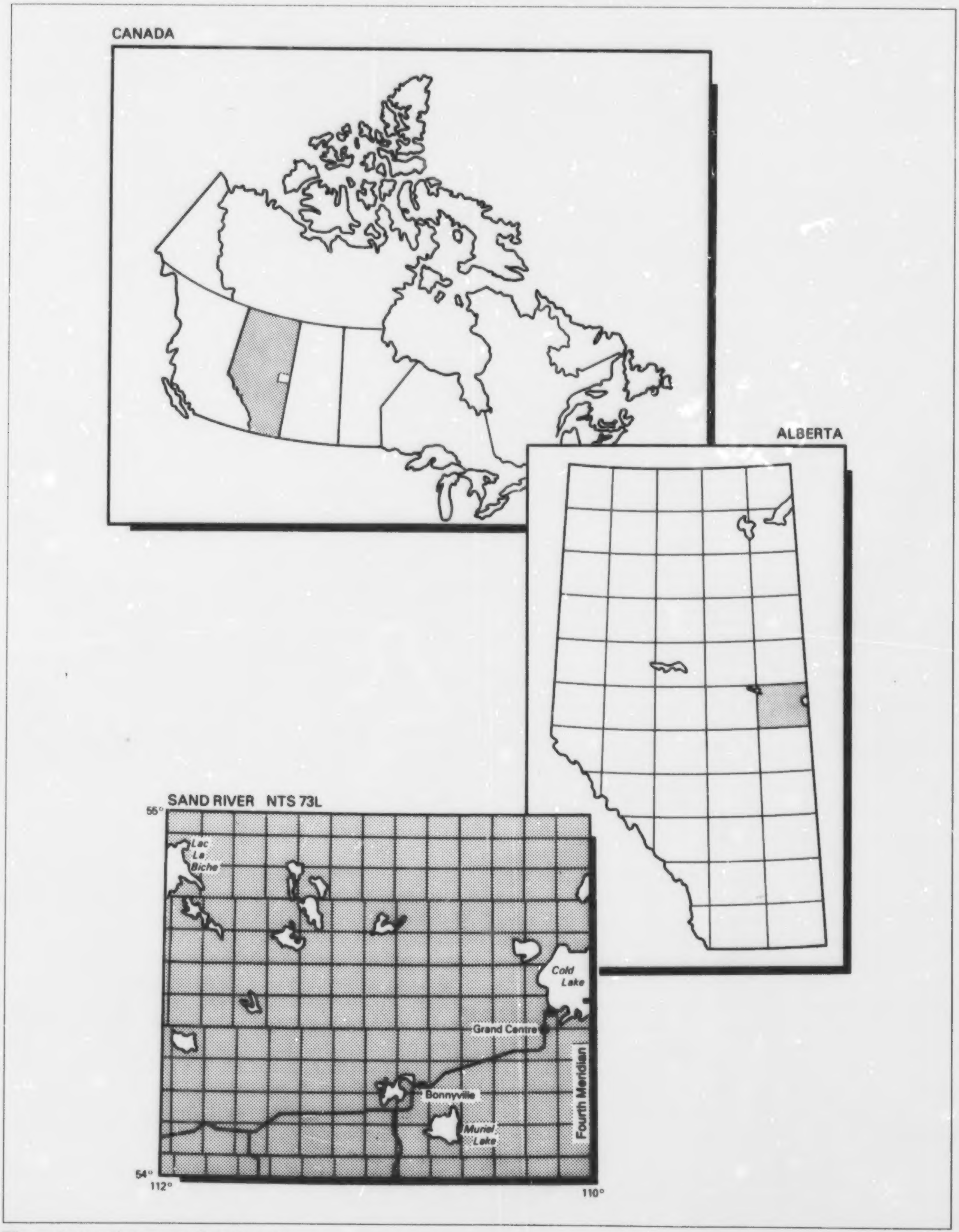
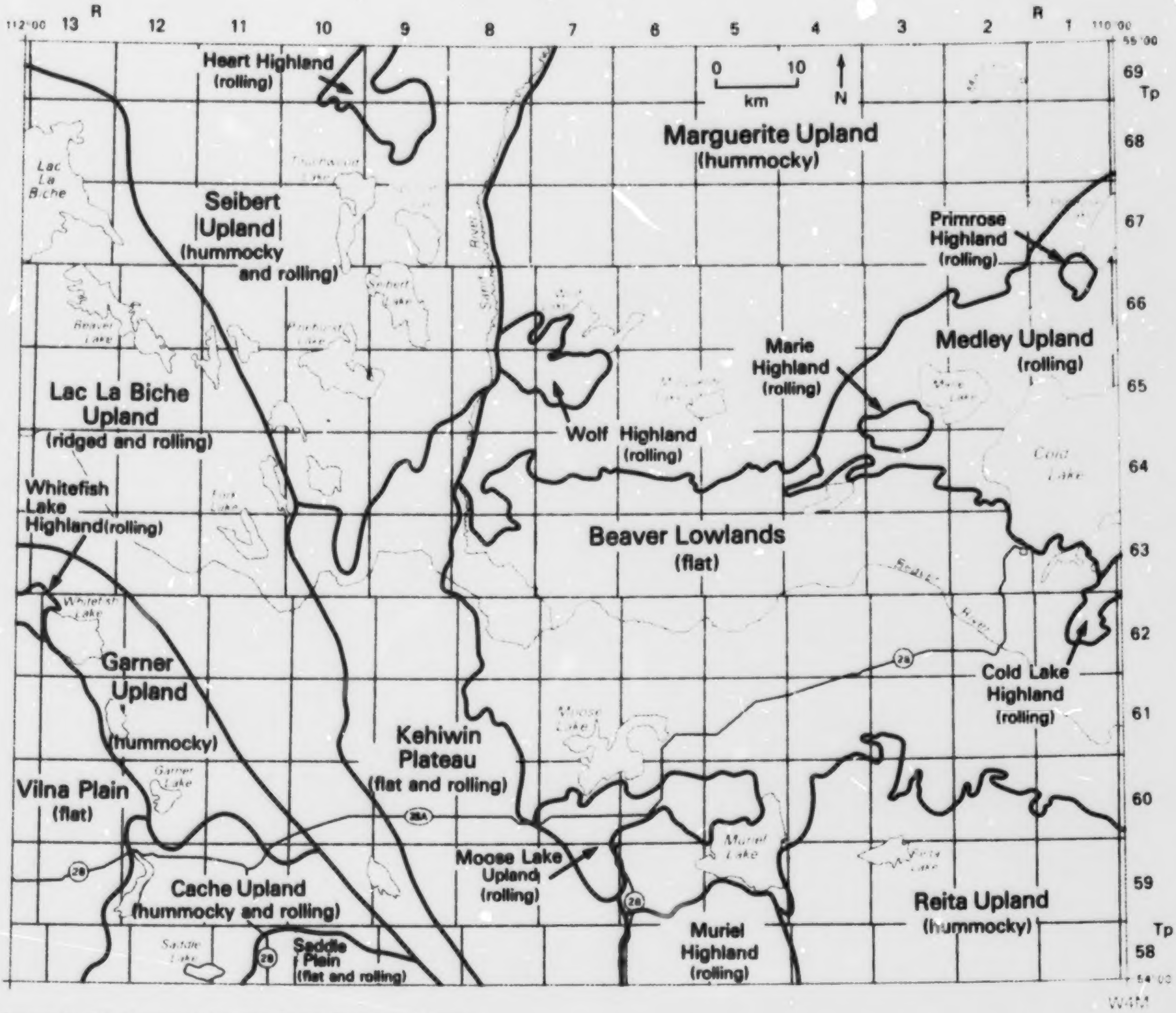

CANADA
ALBERTA
SAND RIVER NTS 73L
55°
54°
112°
110°
Lac La Biche
Cold Lake
Grand Centre
Bonnyville
Muriel Lake
Fourth Meridian

Figure 1. Location maps of study area.


112°00
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13
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W4M
Heart Highland (rolling)
Marguerite Upland (hummocky)
Lac La Biche
Seibert Upland (hummocky and rolling)
Primrose Highland (rolling)
Beaver Lake
Medley Upland (rolling)
Marie Highland (rolling)
Lac La Biche Upland (ridged and rolling)
Wolf Highland (rolling)
Cold Lake
Whitefish Lake Highland(rolling)
Beaver Lowlands (flat)
Whitefish Lake
Beaver River
Garner Upland (hummocky)
Cold Lake Highland (rolling)
Moose Lake
Kehiwin Plateau (flat and rolling)
Garner Lake
Vilna Plain (flat)
28A
28
Muriel Lake
Reita Lake
Moose Lake Upland (rolling)
Cache Upland (hummocky and rolling)
Reita Upland (hummocky)
Saddle Lake
Saddle Plain (flat and rolling)
Muriel Highland (rolling)
Sand River

Figure 2. Physiography of the Sand River map area.

mocky, stagnant-ice topography with numerous wetlands.

The Reita and Moose Lake uplands form the southern margin of the Beaver Lowlands. These uplands range in elevation from 580 m to about 700 m and are characterized by hummocky to rolling terrain with moderate to high relief. Two meltwater channels, here called the Kehiwin and Muriel Lake channels, once drained southeast within these uplands.

The western boundary of the Beaver Lowlands is defined by the Kehiwin Plateau (figure 2). The unit ranges in elevation from 580 to 640 m and is characterized by flat to rolling glacially streamlined terrain.

Three higher relief uplands, differentiated primarily by morphology, lie to the west and north of the Kehiwin Plateau; the Lac La Biche, Garner, and Seibert uplands (figure 2). The Lac La Biche Upland ranges in elevation from 640 m to about 670 m and is characterized by ridged to rolling glacially streamlined terrain with ridges oriented in a northwest-southeast direction. The Garner Upland lies at a slightly lower elevation, ranging from 610 to 640 m, and is characterized by hummocky, glacially thrust terrain, with individual hummocks decreasing in size southeastward from about 1 km^2 in area and 30 m high, to about 0.1 km^2 in area and 3 m high. The Seibert Upland ranges in elevation from 610 m along its southern margin to as high as 760 m near Heart Lake (just north of the map area), though generally it lies below 670 m. It is characterized by large hummocky to rolling landforms that have a glacially streamlined north-south orientation along the Sand River.

The southwest corner of the map area is characterized by lower-relief landforms that differ mainly in morphology. Two plains are present, the Vilna and the Saddle plains, separated by a hummocky to ridged upland, the Cache Upland (figure 2). The Vilna Plain lies at an elevation ranging from 640 to 670 m and is characterized by flat to rolling low-relief terrain. Its eastern margin is bounded by a series of north-south ridges, which form the western scarp of the Cache Upland. The Saddle Plain has a transitional boundary with the Cache Upland and is characterized by a series of east-west oriented hummocks, lying within an otherwise flat to rolling low-relief terrain.

A number of landforms that are smaller in area but higher in relief lie within the major uplands in the study area. These include the Cold Lake, Marie, Primrose, and Wolf highlands in the northeast, the Muriel Highland in the southeast, the Whitefish Lake Highland in the west, and the Heart Highland in the northwest (figure 2). These highlands owe their origin, in part, to glacial thrusting, and are characterized by high relief ridged to hummocky to rolling terrain. Commonly, an abrupt scarp forms the southern margin of the highlands, making them conspicuous when viewed from the south. Relief within these highlands is at least 100 m and locally is as much as 200 m.

Bedrock geology of the study area

In this study the term 'bedrock' is defined as all lithified clastic sediment that underlies the early Tertiary erosional surface. It does not include unconsolidated clastic sediment of late Tertiary age, commonly referred to as 'Tertiary sand and gravel,' or 'Saskatchewan sand and gravel.'

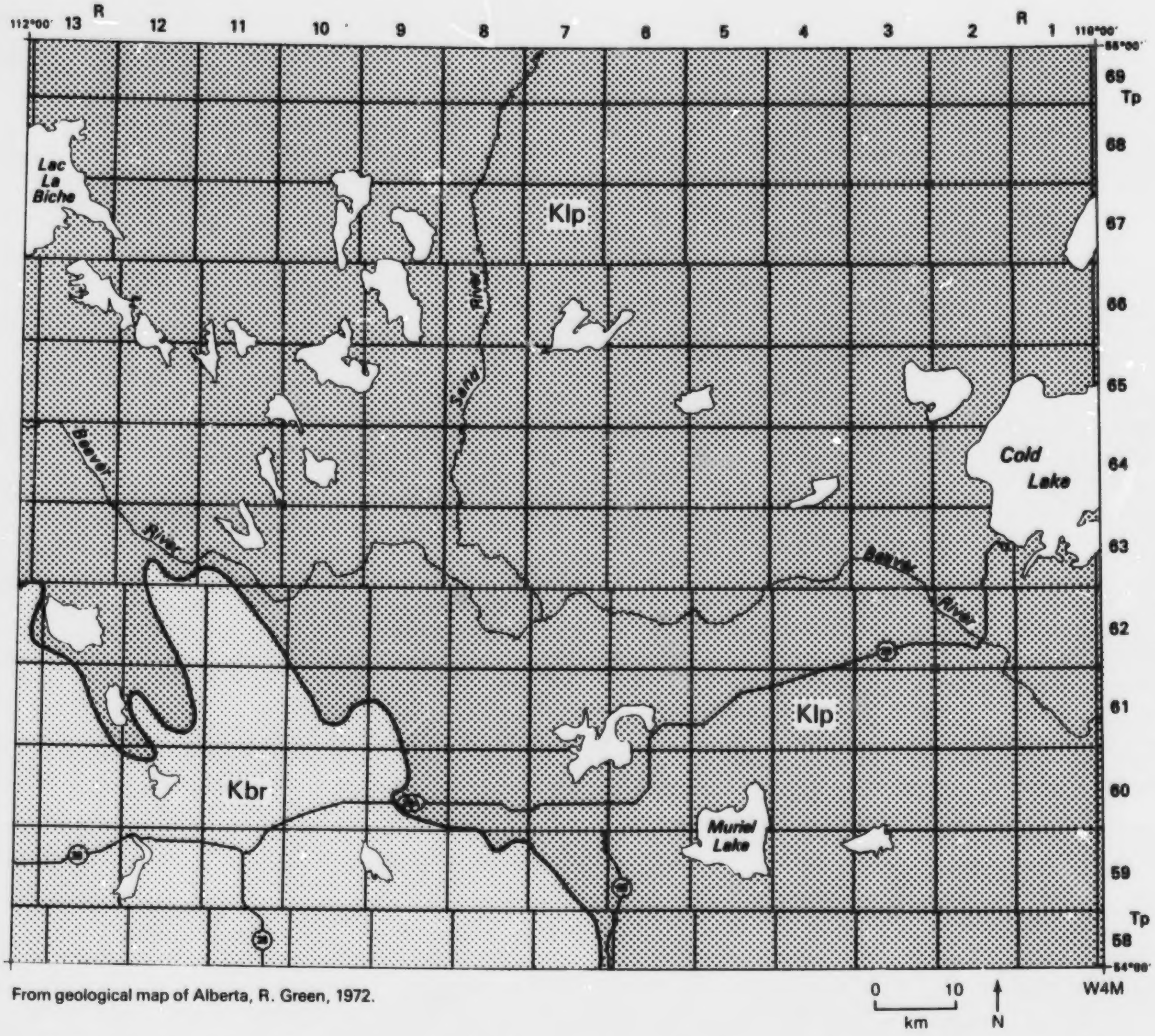
The bedrock in the Sand River map area consists of two Upper Cretaceous formations: the Lea Park Formation (Allan 1918), which underlies the entire map area, and the Belly River Formation (Dawson 1883), which overlies the Lea Park Formation in the southwest corner (figure 3).

Over most of the east-central part of the province the uppermost part of the Lea Park Formation consists predominantly of gray marine claystone which contains differing amounts of silt and sand, ironstone concretions, and bentonite layers (Hume and Hage 1941; Shaw and Harding 1949). The formation ranges in thickness from 135 to 245 m and thickens to the northeast, "as a result of successive lensing-out of several deltaic sand members of the Belly River Formation" (Shaw and Harding 1949, 488). In places, the upper part is yellowish brown (Allan 1918), but where it was recognized in the test holes in the Sand River map area, it is dark gray (5Y 3/1, Munsell color scale). The formation is believed to outcrop along part of the Kehiwin and Beaver River valleys, but in this study it was recognized mainly in rotary and auger test hole samples and electric-log responses. The upper part of the Lea Park Formation is generally soft and poorly lithified. It is easy to penetrate with an auger and this makes it difficult to differentiate from Pleistocene fine-grained lake or stream sediment. Auger samples of the claystone are generally brittle to crumbly and have a waxy appearance when cut. Commonly, inclusions of lighter, buff-colored noncalcareous claystone are present.

The top of the Lea Park Formation is gradational and conformable with the overlying Belly River Formation. Marine claystone of the Lea Park Formation interfingers with deltaic sand of the Belly River Formation, to form a "stair-stepped" contact (Shaw and Harding 1949, 488). In the east-central part of the province the Belly River Formation is differentiated into a number of members (Shaw and Harding 1949), but where undivided, the formation consists of "a series of gray to brownish gray to greenish gray, argillaceous, bentonitic sand closely interbedded with brownish gray to gray, carbonaceous shales and silts. Thin carbonaceous layers are characteristic of the normal facies. Thin coal seams characterize the continental to marine transition facies" (Shaw and Harding 1949, 491). The formation is about 210 m thick near Edmonton but pinches out to the northeast.

In this study, sandstone of the Belly River Formation was not recognized in outcrop nor within any of the auger test holes. The difficulty in recognizing the Belly River Formation in the west is attributed in part to its gradational contact with the Lea Park Formation and to the similarity of its sand composition to that of the overlying sand in unit 1 of the Empress Formation. Furthermore, glacial thrusting within the buried Kikino and Beverly valleys in the southwest corner of the map area has displaced as much as 60 m of sandstone, claystone, and coal from the Belly River Formation. In these areas, it is difficult to be certain if bedrock-type sediment encountered within a test hole is in place or has been moved.

Because of the difficulty in establishing the contact between Lea Park Formation and Belly River Formation, the contact shown in the geologic cross sections (in pocket) is chosen from the Geology Map of Alberta (Green 1972). This contact is believed to dip to the southwest at about 4 m/km.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From geological map of Alberta, R. Green, 1972.

Kbr BELLY RIVER FORMATION: gray to greenish gray, thick-bedded feldspathic sandstone; gray clayey siltstone, gray and green mudstone; concretionary ironstone beds; nonmarine

Klp LEA PARK FORMATION: dark gray shale; pale gray, glauconitic, silty shale with ironstone concretions; marine

Figure 3. Bedrock geology of the Sand River map area.

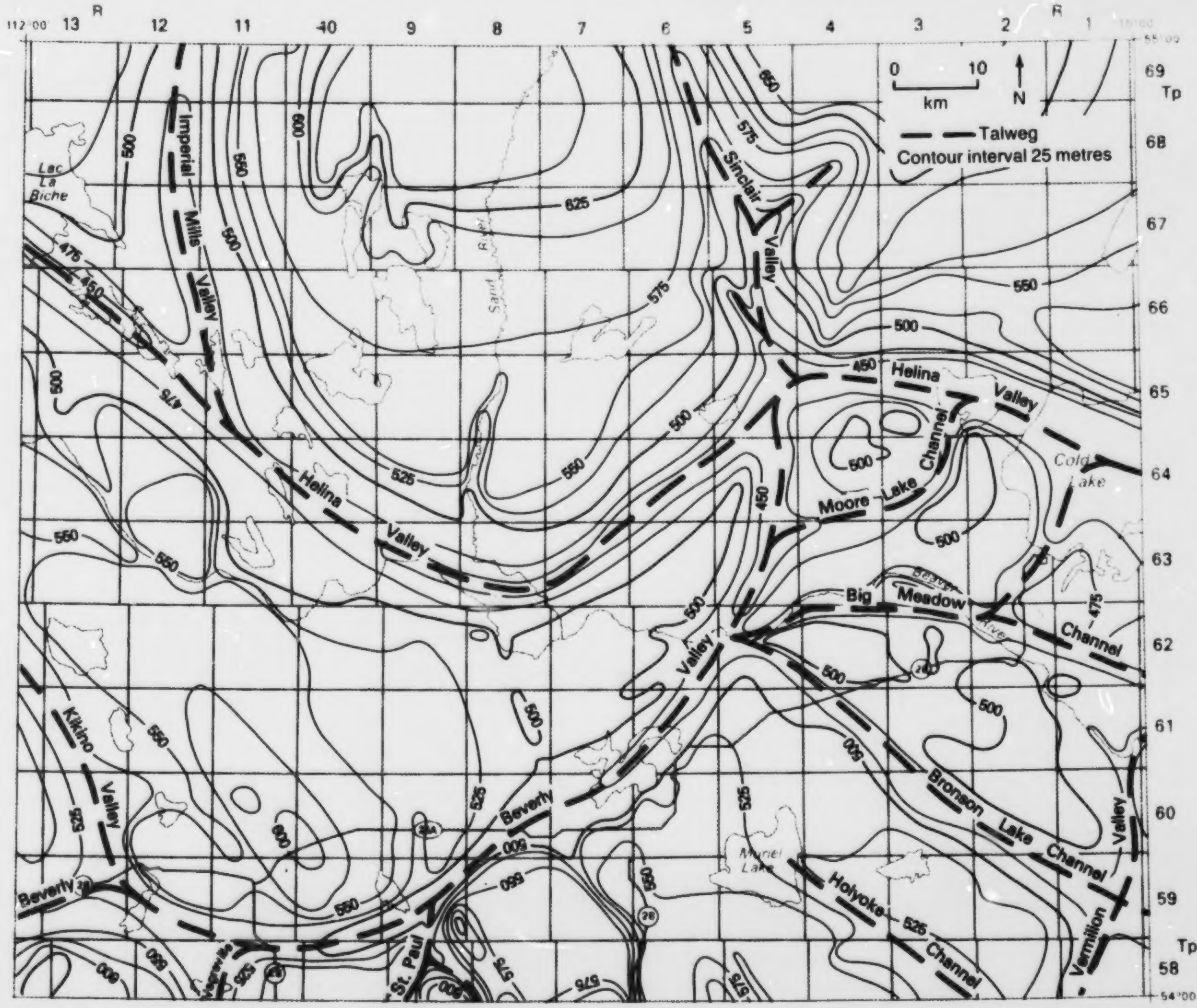
Bedrock topography, and buried valleys and channels

Introduction

During the Laramide Orogeny in western Alberta, regional uplift produced a northeastward slope through the plains of central Alberta. Erosion from the Eocene through to the Pliocene later removed much of the Upper Cretaceous sediment, forming large valleys. In the western and northern parts of the province, the uplands were mantled by thick fluvial gravel. Elsewhere in the east-central part of the province, this gravel-cap was much less extensive or absent.

Within the Sand River map area, the highest bedrock landforms are mapped at an elevation of about 650 m (figure 4). Drainage from these uplands was channeled into two major valleys, the Beverly and Helina valleys. The bedrock surface lies at its lowest elevation, about 425 m, within the Helina Valley, along the eastern edge of the map area. During Pleistocene time, meltwater during several glaciations eroded additional valleys into the bedrock surface. Till and stream sediment now mask most of this underlying bedrock topography.

Numerous studies of the bedrock topography and buried valleys have been done both within the map area and in surrounding areas. Stalker (I961, 1967) conducted studies in central Alberta and mapped the buried North Saskatchewan Channel near Edmonton. The name was changed to Beverly Channel by Carlson (1967) in his detailed map of the bedrock topography in the Edmonton area, and later was referred to as the Beverly Valley in the eastern part of the Tawati-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Imperial Mills Valley
Sinclair Valley
Helina Valley
Moore Lake Channel
Cold Lake
Big Meadow Channel
Beaver River
Valley
Kikino Valley
Beverly Valley
Bronson Lake Channel
Vermilion Valley
Holyoke Channel
Muriel Lake
Vegreville
St. Paul
Sand River
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475
500
525
550
575
600
625
650

Figure 4. Bedrock topography of the Sand River map area.

naw map area (Carlson 1977). Farvolden (1963) prepared a bedrock topography report for the Edmonton and Red Deer area and defined two major buried valleys that extend into the southern part of the Sand River map area: the Vegreville and Vermilion valleys. These two valleys were more clearly defined by Carlson and Currie (1975) in the bedrock topography map of the Vermilion map area. Christiansen and Whitaker (1974) mapped the bedrock topography and buried valleys directly east of the study area in the Waterhen map area of Saskatchewan. They show two buried valleys entering the Sand River map area: the Bronson Lake Valley in the southeast corner, and the Hatfield Valley, which is believed to enter beneath Cold Lake.

The first major study of buried valleys in the Sand River map area was done by Yoon and Vander Pluym (1974) who mapped the Beverly Valley and two other major buried valleys, the Helina and Kikino valleys. Gold (1978) later defined the stratigraphy and history of the deposits within these buried valleys. More recently, a 1:250 000 bedrock topography map of the Sand River map area was produced jointly by the Alberta Research Council and Alberta Environment (Gold and others 1983).

Buried preglacial valleys

The major preglacial valleys are characteristically broad, with low gradients and shallow valley-wall slopes. Sediment on the floors of these valleys consists of sand or gravelly sand that is composed predominantly of quartzite and chert clasts derived from the Rocky Mountains and plains areas of Alberta. Granitic clasts from the Canadian Shield are absent. Two major buried preglacial valleys and their associated tributaries are present within the study area: the Helina and Beverly valleys.

Helina Valley and tributaries

The Helina Valley (Yoon and Vander Pluym 1974) is the deepest and widest buried valley in the map area (figure 4). It enters the northwest corner of the study area beneath Lac La Biche, trends southeast to Tp 63, R 8, and then swings northeast, extending beneath Cold Lake and ultimately joining the Hatfield Valley in Saskatchewan (Whitaker and Pearson 1972). Gold (1978) suggested that the Helina Valley may have once contained the preglacial Athabasca River.

The contour lines in figure 4 show that the central and eastern segments of the Helina Valley slope northeast, whereas the northwestern segment slopes northwest. This reversal in gradient direction may be attributed to stream capture of the Helina drainage system during its development, which caused flow to be in opposite directions during the valley's history. However, it is difficult to accurately define the valley depth and width in that area, and it is more likely that the reversed gradient is only an apparent one, resulting from insufficient data. The depth, width, and estimated gradient of the talweg are summarized in table 1.

Table 1. Estimated gradients of talwegs, and depths and widths of the steeper middle parts of buried valleys and channels in the Sand River map area.

Preglacial valleys	Width (km)	Depth (m)	Gradient (m/km)
Helina	8-12	35-65 average 50	0.25 to northeast
Imperial Mills	4.5-6.5	uncertain	uncertain
Sinclair	8-10	40-70	1.0 at south end
Vermilion	3-5	35	1.7 near head of valley
Beverly	5-8	45-60	0.5 to northeast
Vegreville	2.5-6	30	1.3 near head of valley south of map area
Kikino	average 3-5 maximum 8	average 30 maximum 90	0.5-1.0 in northwest, unknown in southeast
St. Paul	1-1.5	25	3.0 in west branch
Glacial Channels			
Moore Lake	2-3	average 35 60 in west end	uncertain
Big Meadow	1-3	15-25	uncertain
Bronson Lake	1.5-3	30-45	1.3 to northwest
Holyoke	1-2	115-20	uncertain

Three tributaries of the Helina Valley are recognized in the map area: the Imperial Mills, Sinclair, and Vermilion valleys (figure 4). The Imperial Mills Valley enters in the northwest part of the map area and trends south for a distance of 40 km to join the Helina Valley in Tp 65, R 11 (figure 4). The north end of the valley extends into the Winnefred Lake map area where it is believed to join the buried Wiau Valley (Gold, personal communication; Gold 1983). The Imperial Mills Valley may have resulted from stream capture that diverted flow south from Wiau Valley into the Helina Valley. The estimated width, depth and gradient of the valley are summarized in table 1. A broad low in the present land surface near the settlement of Imperial Mills is the only present topographic expression of the valley.

Sinclair Valley is located east of Wolf Lake in the northeast corner of the map area (figure 4). The valley enters from the north and slopes southeast for a distance of about 45 km to join the Helina Valley in Tp 65, R 4. The headwaters are believed to be confined to the uplands north of the Helina Valley, and the steep gradient indicates that it may be a younger tributary. The estimated depth, width, and gradient are summarized in table 1.

The Vermilion Valley enters in the southeast corner of the map area (figure 4). It slopes northward to about Tp 61, R 1, where it extends beyond the map area into Saskatchewan. The valley has its headwaters in the plains region of central Alberta (Carlson and Currie

1975), and although it is probably a major tributary of the Helina system, the junction of these two valleys has not been clearly defined. It is likely that the two merge in Saskatchewan, directly east of the Sand River map area, but in the absence of data in that area, it is conceivable that the Vermilion Valley joins the nearby Hatfield Valley instead. The estimated width and depth are summarized in table 1. The information is insufficient to calculate the gradient of the valley within the map area, but Yoon and Vander Pluym (1974) calculated a gradient of 1.7 m/km at the head of the valley southwest of the study area.

Beverly Valley and tributaries

Beverly Valley is the second deepest and widest buried valley in the map area. The valley enters in the extreme southwest, and slopes essentially north and east to Tp 65, R 5, where it merges with the Helina Valley (figure 4). The Beverly Valley is almost certainly the preglacial valley of the ancestral North Saskatchewan River. This system has been mapped as far west as the foothills of the Rocky Mountains (Stalker 1961; Farvolden 1963; Carlson 1967, 1977). Compared to the Helina Valley, the Beverly Valley is narrower, with steeper walls and a steeper gradient (table 1), all of which suggest that it is younger. The geometry of the confluence of the two valleys, shown in figure 4, indicates that the Beverly Valley was once a tributary of the Helina Valley. Segments of the Beverly Valley also carried glacial meltwater but the valley is now completely buried by Pleistocene sediment.

The Vegreville and St. Paul valleys, and possibly the Kikino Valley, were once tributaries of the Beverly Valley (figure 4). Vegreville Valley enters near Saddle Lake in the southwest, and extends northward for a distance of about 8 km to join with the Beverly Valley in Tp 58, R 11 (figure 4). Near this junction, the Vegreville Valley is wide and poorly defined, whereas nearer to the headwaters in the plains southwest of the study area, Farvolden (1963) described the valley as being narrow with steep banks. Farvolden (1963) considered the stratified sediment at the valley floor to be Tertiary fluvial sediment derived from highlands adjacent to the channel. However, drill records and samples of a thick (60 m) Pleistocene sequence within the valley along the northern segment show the presence of glaciofluvial sediment (Alberta Research Council test hole information, Mougeot, personal communication). This indicates that segments of the Vegreville Valley were occupied by glacial water.

The St. Paul Valley is characterized by two branches that enter in the southwest part of the map area but which merge to join with the Beverly Valley at Tp 59, R 9 (figure 4). Both branches are narrow and shallow (table 1). The history of the St. Paul Valley is uncertain; it was eroded prior to the last glaciation, evidenced by glacial sediment on the valley floor, the Bronson Lake Formation, that was deposited during an early glaciation in the study area.

The Kikino Valley lies along the western boundary of the map area (figure 4). It extends southeast for a distance of about 30 km to join with the Beverly Valley in Tp 59, R 13. Like the Imperial Mills Valley, the Kikino Valley connects two major valleys, the Beverly and Helina valleys. Gold (1978) suggested that the Kikino Valley was eroded immediately before glaciation in the southwest part of the map area. He argued that as the first glacier in the area advanced southwest it blocked the preglacial North Saskatchewan River in the Beverly Valley. This blockage diverted water northwest towards Lac La Biche along a newly eroded channel (Kikino Channel) that paralleled the glacier margin. Gold and others (1983) later concluded that the glacier could equally as well have blocked the drainage in the Helina Valley, thereby diverting the ponded water to the southeast and eroding the Kikino Valley. The interfluve between the Helina and Beverly valleys is shallow within the eastern part of the Tawatinaw map area, directly west of the Sand River map area, and could have been easily breached by southeast flow from the Helina Valley. The geometry of the junctions of the Kikino Valley with both the Helina and Beverly valleys (Carlson 1977; and figure 4) also supports this hypothesis. The southeast segment of the Kikino Valley appears to slope toward the Beverly Valley, indicating at one time flow was from northwest to southeast. At the north-west end of the Kikino Valley however, flow was in the opposite direction, toward the Helina Valley, shown by the contours in the bedrock topography map of the Tawatinaw map area (Carlson 1977). Presumably, this occurred after the glacier margin retreated and the regional drainage within the Helina Valley was reestablished.

Although the above hypothesis assumes a nearby glacier margin for the creation of the Kikino Valley, the substantial width of the valley, compared to that of other glacial channels, indicates that the Kikino Valley formed over a much longer period than during a short-lived glacial event.

Buried glacial channels

Segments of the preglacial valleys probably served to drain glacial meltwater during the Pleistocene. A number of buried channels in the map area, however, are considered to have been formed by rivers in contact with, or adjacent to a glacier margin. During glaciation, drainage within the preglacial valleys was severely disrupted and in some cases permanently altered by blockage with ice. Stratigraphic evidence (see descriptions of unit 3 of the Empress Formation and the Bronson Lake Formation) indicates that during the first glaciation in the area, here named the Cherry Grove Glaciation, a series of ice-marginal channels was eroded into the bedrock surface. This erosion resulted from both drainage diverted out of the preglacial valleys and meltwater issuing from the glacier. These glacial channels are recognized by the following features: (1) most, though not all, of the channels are oriented in a general northwest-southeast direction which is perpendicular to the northeast trend in regional drainage; (2) the channels are generally narrow and have steep walls, indicating that they functioned for a short period of time; and (3) fluvial sediment on the floor of the channels contains abundant clasts derived from the Canadian Shield, which indicates a Laurentide glacial source.

At least four major buried glacial channels have been recognized, all within the eastern part of the map area. These are: the Moore Lake, Big Meadow, Holyoke and Bronson Lake channels (figure 4). In the 1:250 000 bedrock topography map of the Sand River map area (Gold and others 1983), the Moore Lake Channel was unnamed, whereas the Big Meadow, Holyoke, and Bronson Lake channels were referred to as 'valleys'. The estimated widths, depths and gradients of the talwegs of these channels are summarized in table 1.

Moore Lake Channel, a small channel located west of Cold Lake, joins with the Beverly and Helina valleys. The floor of the channel generally lies at a higher elevation than the base of the Beverly Valley, except near the junction at Tp 63, R 4-5, where the floor of the Moore Lake Channel is over-deepened and is lower than that of the Beverly Valley.

The Big Meadow Channel lies within the eastern part of the Beaver Lowlands and joins with the Beverly Valley in Tp 62, R 5, essentially at the same junction as that of the Bronson Lake Channel and the Beverly Valley (figure 4). From this western junction the Big Meadow Channel slopes eastward to Tp 62, R 2 where it divides; one branch swings northeast to join the Helina Valley beneath Cold Lake, and the other branch continues east, likely joining the Vermilion Valley in Saskatchewan.

The Bronson Lake Channel extends southeast from its junction with the Beverly Valley in Tp 62, R 5 and apparently intersects the Vermilion Valley in Tp 59, R 1. The valley extends eastward into Saskatchewan, where it was first mapped (Whitaker and Pearson 1972; Christiansen and Whitaker 1974). Drill records at the western segment of both the Big Meadow and Bronson Lake channels describe the valley floor sediment as composed of 'preglacial' sediment, mainly quartzite and chert. Further east along these channels, however, drillers' field logs describe the stratified sediment as containing granitic clasts, indicating a glacial source of sediment. If the drillers' descriptions can be considered accurate, the presence of 'preglacial' sediment on the valley floors probably indicates that drainage in the Beverly Valley was blocked and diverted southeast, probably along the advancing Cherry Grove Glacier margin. Conceivably, sediment on the floor of the Beverly Valley was eroded and redeposited at the heads of these newly eroded channels. Glaciofluvial sediment, containing granitic clasts, was deposited farther east along the channels by meltwater issuing from the glacier margin.

The western end of Holyoke Channel has not been determined, though it may lie beneath Muriel Lake in Tp 59, R 5. The channel extends southeast out of the map area in Tp 58, R 3, and probably merges with the preglacial Vermilion Valley beneath Frog Lake in Tp 56, R 2.

Pleistocene stratigraphy

Introduction

The Sand River map area is a part of Alberta where the Pleistocene sequence is not only complex but also well preserved. Although the sequence is generally thick (more than 50 m) compared to most areas in central Alberta, only the upper 10 m or so are exposed, primarily in river channels and road cuts. As a result, most of the stratigraphy is defined by subsurface data.

Eight Pleistocene formations are recognized in the Sand River area. Four that contain glacial diamicton[1] and four that do not, are differentiated on the basis of stratigraphic position, grain size, lithic composition, outcrop properties and geophysical properties, including drilling characteristics. Descriptions are given for each formation under separate chapter headings. These descriptions include type section, grain size and lithic composition, distribution of unit, the differentiating properties, nature of contacts and origin.

Sources of data

Four sources of subsurface data, ranked below in the order of their importance, were used in this study. More than 900 test holes drilled by government agencies, such as Alberta Environment and the Alberta Research Council, private oil companies, and water-well drilling companies were used (figure 5). The primary source of data consists of field log descriptions and about 2500 samples collected from 110 auger test holes drilled by the Geological Survey Department of the Alberta Research Council (referred to here as "the Survey") in 1976 and 1977 (figure 5). These test holes have two designations. Test holes labelled "T", followed by a number (T32, for example) were drilled in 1976, primarily in the east half of the map area. Test holes labelled "77SR", followed by a number, (77SR9, for example) were drilled in 1977, mainly in the west half of the map area.

At each test hole, samples were collected and logged at 1 m intervals off a continuous-flight auger that, in most cases, was capable of penetrating to a depth of about 50 m. Laboratory analyses of the samples were used, along with the field log descriptions, to differentiate and correlate the glacial diamicton (till) units. The log descriptions of each test hole, as well as a table of the analytical data, are available as Alberta Research Council's Open File Report 1979-6 (Andriashek and Fenton 1979). Because of the great thickness of the surficial deposits, the auger was capable of drilling through the complete Pleistocene sequence in only 14 of the 110 test holes. Consequently, the Survey's test hole data were useful for defining only the upper one-half to two-thirds of the stratigraphic sequence.

The next most important source of stratigraphic data was provided by Alberta Environment from its groundwater and buried channel investigations in the Sand River map area. This information consists of good quality electric logs, field log descriptions, and information from drill cuttings and side-wall samples. In this study the Alberta Environment test holes are designated by a capital "E", followed by a number (E802, for example). Gold (1978) analysed the side-wall samples from 78 of these test holes in his study of the Pleistocene stratigraphy in the buried channels in the Sand River map area. Some of Gold's analytical results, particularly the grain-size data, very-coarse-sand composition, and carbonate content of the silt-clay fraction, are used to define the lowermost till units in this study. One advantage of Gold's analytical data is that they are supplemented by electric logs. This enables correlations to be made with the electric-log data from the water-well drillers.

Test hole information from water-well drillers proved to be useful in extending the correlations of the stratigraphic units in those areas where analytical data were absent. This information consists of drillers' log descriptions and, in some places, electric logs. Electric logs supplied by Chomey Drilling, Elk Point Drilling, and McAllister Drilling were most useful because their logs are sensitive enough to record the differences in the electrical properties of the glacial diamicton (till) units.

Oil-company geophysical logs provided the least useful stratigraphic data on the Pleistocene sequence. The logs are not sensitive enough to record differences in the glacial diamicton units but can be used to map the buried coarse sand and gravel units. Furthermore, the upper 15 m of these test holes commonly are not logged, and the upper Pleistocene sequence is not recorded. One exception is the information from structure test holes drilled throughout much of the province in the mid-1950s. In many places these logs were recorded from the surface and record subtle differences in the electrical properties of the glacial diamicton (till) units. These logs are not differentiated from the other oil-company logs shown in figure 5.

Discussion of methods

In this study the identification and differentiation of units within a stratigraphic sequence was accom-

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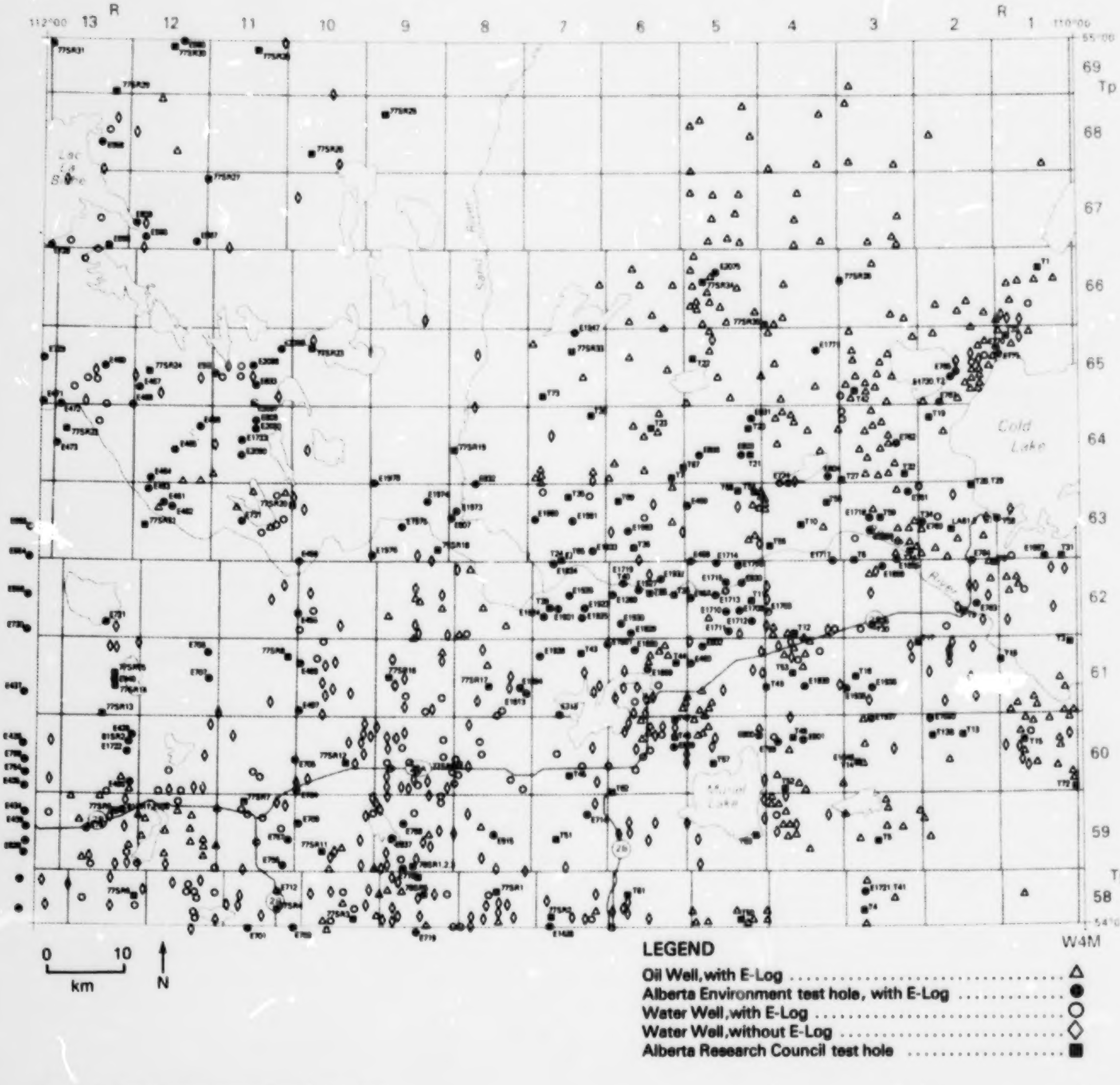
[1] In this report, diamicton is a nongenetic term to describe nonlithified, nonsorted or poorly sorted sediment that can contain particles ranging in size from clay to boulders. The proportion of material within each particle size is not restricted but can differ in diamictons of different stratigraphic units (for example, sandy diamicton in which a greater amount of material is present in the sand fraction).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Alberta Environment test hole, with E-Log .... ●
Water Well, with E-Log .... ○
Water Well, without E-Log .... ◇
Alberta Research Council test hole .... ■

Figure 5. Distribution map of test hole data.

plished using both laboratory data and field observations (Andriashek and Fenton 1979; and appendix A). This includes the following information: (1) lithologic properties, such as color, grain size of the smaller-than-gravel fraction, moisture content, structure, stratification, partings, inclusions, joints, pebble orientations, and nature of contacts; (2) mineralogic and petrologic properties, such as composition of the very-coarse-sand fraction, pebble lithology, and carbonate content of the silt-clay fraction; (3) geophysical properties, recorded by electrical resistivity and self-potential, and gamma radiation; and (4) miscellaneous properties, such as palynology of bedrock samples. Detailed descriptions of the analyses of these properties and a description of the application of these properties in defining formations containing glacial diamicton are provided in appendix A.

A number of laboratory analyses were performed to characterize and differentiate the glacial diamicton units. The sequence of these analyses is depicted in a flow chart (figure 6). The major analyses include grain size of the smaller-than-gravel fraction, carbonate con-

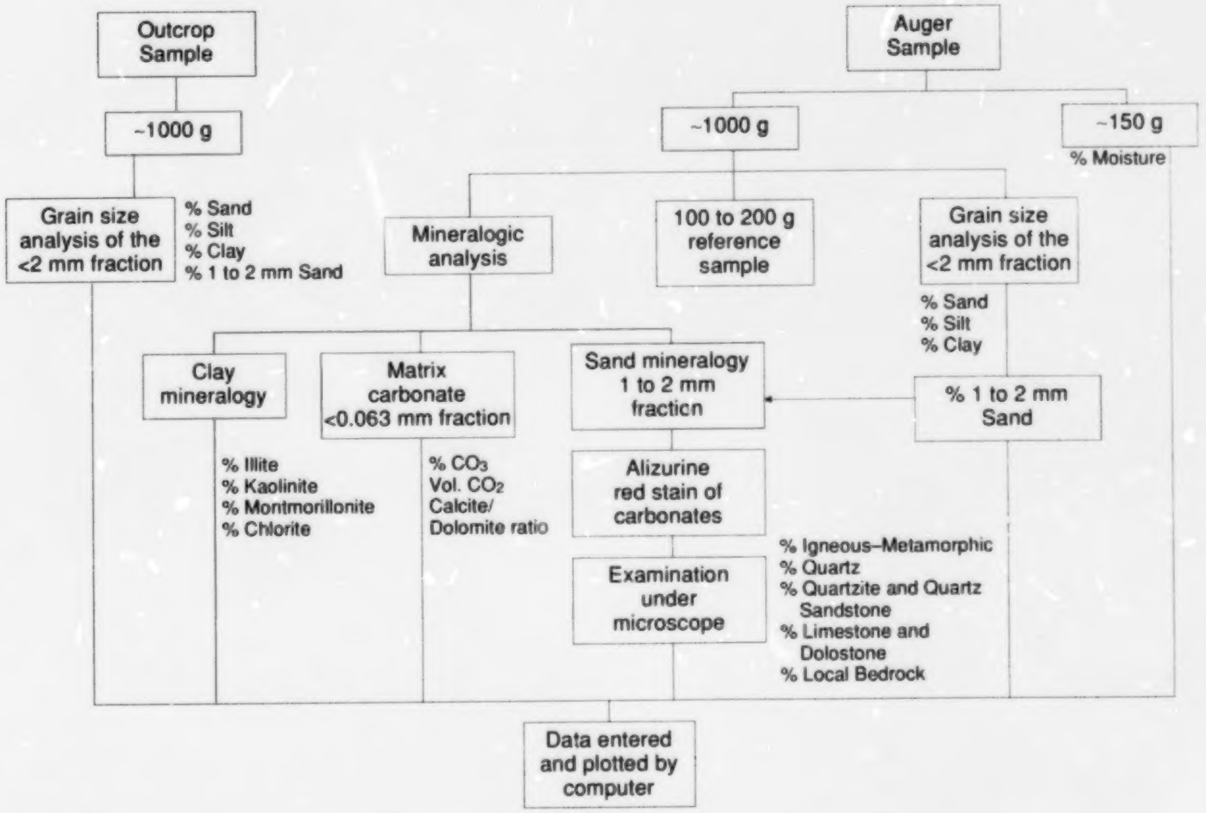

Outcrop Sample
~1000 g
Grain size analysis of the <2 mm fraction
% Sand
% Silt
% Clay
% 1 to 2 mm Sand
Auger Sample
~1000 g
~150 g
% Moisture
Mineralogic analysis
100 to 200 g reference sample
Grain size analysis of the <2 mm fraction
% Sand
% Silt
% Clay
Clay mineralogy
Matrix carbonate <0.063 mm fraction
Sand mineralogy 1 to 2 mm fraction
% 1 to 2 mm Sand
% Illite
% Kaolinite
% Montmorillonite
% Chlorite
% CO3
Vol. CO2
Calcite/ Dolomite ratio
Alizurine red stain of carbonates
Examination under microscope
% Igneous–Metamorphic
% Quartz
% Quartzite and Quartz Sandstone
% Limestone and Dolostone
% Local Bedrock
Data entered and plotted by computer

Figure 6. Flow chart showing the stages of till-sample analysis.

tent of the silt-clay fraction, composition of the very-coarse-sand (1 to 2 mm) fraction, clay mineralogy, moisture content, and a minor amount of palynology. For a given test hole the analytical data were displayed on computer-generated graphs that plot the property against depth. From these graphs, contacts were established where distinct breaks or changes in the properties of the formations were evident. Figure 7 is an example of such plots of the data from three test holes in which formations containing glacial diamicton (till) are recognized. In most places, the contact between the formations is easily defined by abrupt changes in all of the properties, and in some places the formations containing till are separated by stream or lake sediment. In a few areas however, the contact between formations is gradational and only an approximate boundary can be defined. In these cases the boundary was defined at the depth where the very coarse sand has the greatest change in composition. Reliance was placed on sand composition, rather than grain size, mainly because the former appears to be less influenced by local incorporation of underlying material by the glacier.

Simple descriptive statistics were applied to characterize the formations containing glacial diamicton. A normal distribution of the data was assumed, but not tested. For every test hole in which glacial diamicton was present, a sample mean and standard deviation were calculated for each property of the diamicton sequence. These values are shown in tables for each formation containing glacial diamicton (table 3, appendix B, for example). The sample means assisted in characterizing the different formations within an individual test hole and further, were used to correlate diamicton of a given formation with diamicton of what was considered to be the same formation in adjacent test holes.

After completing the correlations, an average or mean of the sample means of each property was calculated for all of the test holes in which the formation was recognized. This mean of the sample means summarizes the general characteristic of each property of the formation in the map area. Nearby geophysical logs, mainly electric logs, were then chosen to qualitatively calibrate the log responses with the analytical properties of the formations. In this way electric logs could be used to correlate formations in those areas where analytical or descriptive information were absent.

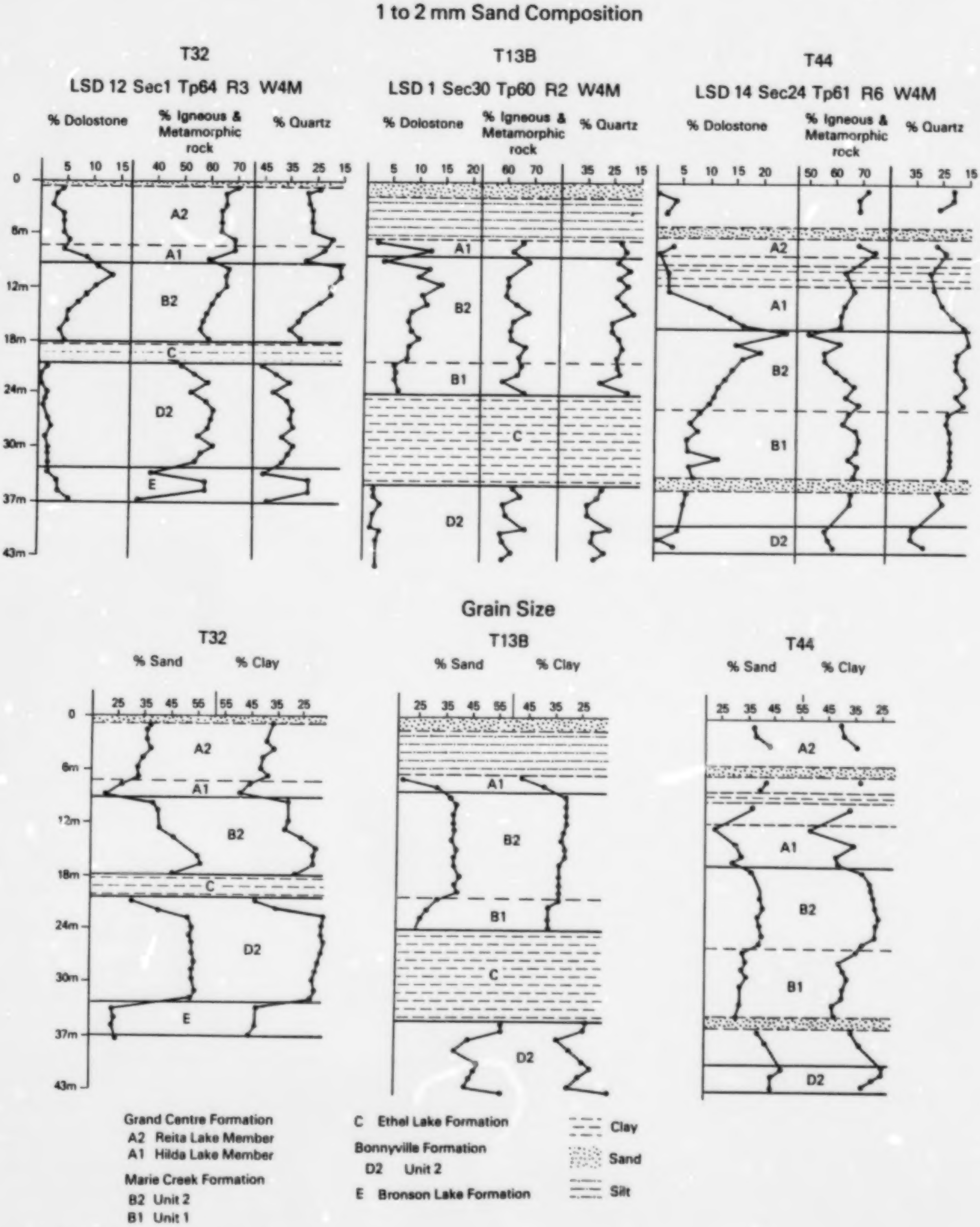


Figure 7. Plots of properties against depth in three example test holes.

Empress Formation

The Empress Formation is recognized within most of the major buried valleys in the Sand River study area. The name of the unit was originally proposed as the Empress Group by Whitaker and Christiansen (1972, 353) to include the "stratified gravel, sand, silt, and clay of fluvial, lacustrine, and colluvial origin that overlies marine Cretaceous and nonmarine Tertiary bedrock and underlies glacial till of Quaternary age in southern Saskatchewan and adjoining areas of Alberta." The name is derived from the town of Empress, Alberta, and the type section for the group is along the east bank of the South Saskatchewan River (LSD 13, Sec 9, Tp 22, R 29, W 3 Mer). Although Whitaker and Christiansen recognized different lithologic units within the Empress Group, they did not assign formal formation names to any of these units. In this study the group status has been lowered to formation status. Until the units within the Empress Group can be clearly defined and mapped as formations, it seems more logical to treat the package as a formation that can be later raised to a group if warranted.

There are no outcrops of the Empress Formation in the map area, but drill records indicate three lithologically distinct units that can be mapped within the formation: unit 1, a basal sand and gravel containing clasts derived only from the Cordillera and local bedrock; unit 2, a middle silt and clay, with minor sand and gravel beds of undetermined composition; and unit 3, an upper glacial sand and gravel with clasts derived from the Canadian Shield (table 2).

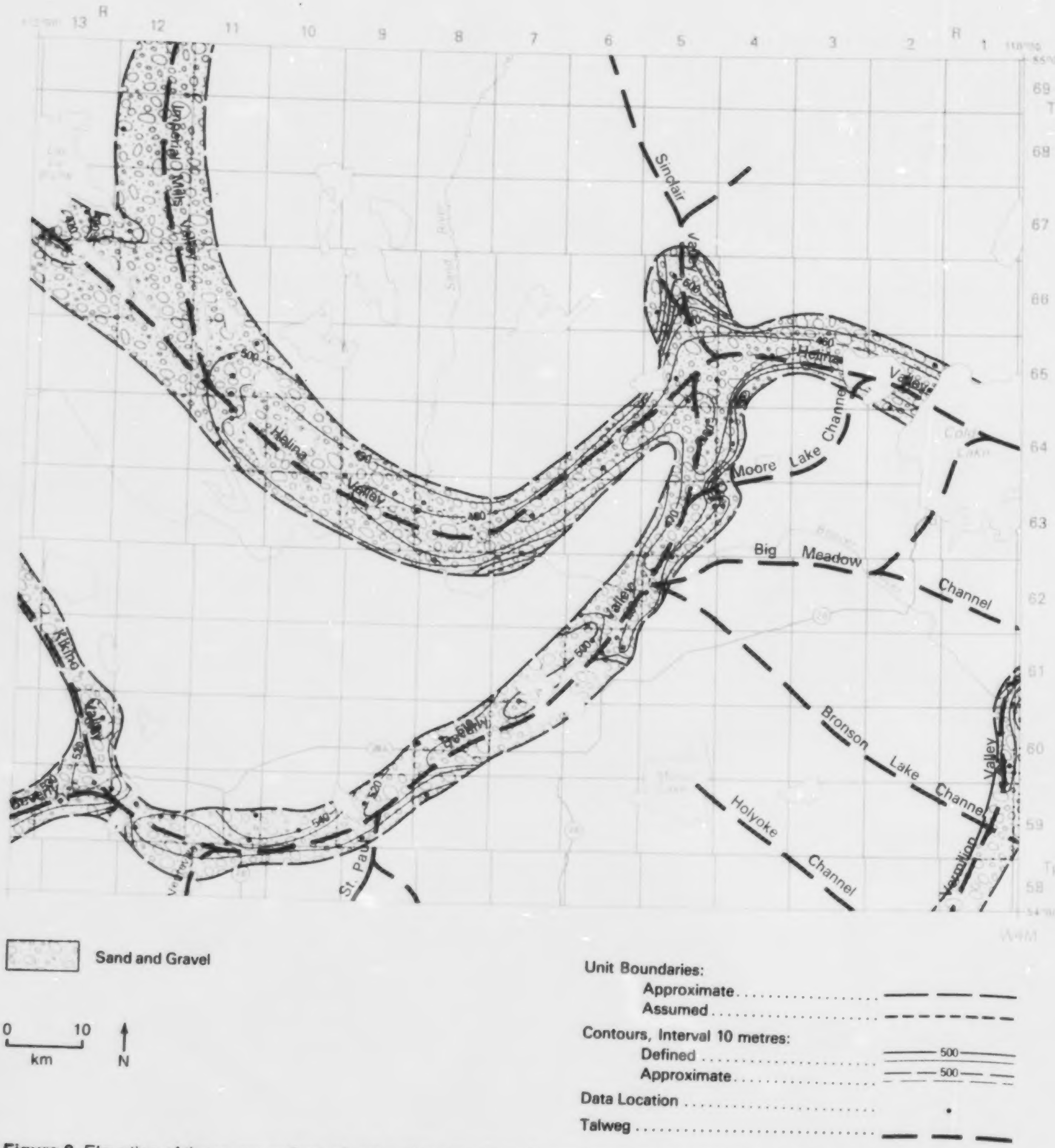
Unit 1: Preglacial sand and gravel

Description of unit

Sand and gravel of unit 1 of the Empress Formation are found on the floors of the buried Helina and Beverly valleys and in some of their tributaries. Drill cuttings and side-wall samples indicate that the unit is composed of clasts derived from either the Cordillera or from the local sandstone. The formation generally consists of thin (<5 m) basal gravel overlain by sand or gravelly sand ranging in thickness from 5 to 10 m. The

Table 2. Quaternary stratigraphy of the Sand River map area.

Unit	Description
Postglacial and Recent Deposits	Stratified clay, silt, sand, gravel of fluvial, lacustrine or eolian origin
Grand Centre Formation	Glacial diamicton (till); very coarse sand rich in igneous and metamorphic rock fragments and poor in quartz and carbonate fragments
Vilna Member	Clayey glacial diamicton (till), commonly contains incorporated masses of glacially displaced sediment
Kehiwin Lake Member	Silty-sand glacial diamicton (till), overlain by stratified sand and gravel in places
Reita Lake Member	Clayey-sand glacial diamicton (till)
Hilda Lake Member	Clayey glacial diamicton (till), commonly contains incorporated masses of glacially displaced sediment
Sand River Formation	Stratified sand and gravelly sand, some silt and clay; glaciolacustrine or glaciofluvial origin
Marie Creek Formation	Glacial diamicton (till); very coarse sand rich in carbonate fragments
Unit 2	Silty-sand glacial diamicton (till)
Unit 1	Clayey glacial diamicton (till)
Ethel Lake Formation	Stratified silt and clay, some sand and gravel; glaciolacustrine origin
Bonnyville Formation	Glacial diamicton (till); very coarse sand rich in quartz fragments and poor in igneous and metamorphic rock and carbonate fragments
Unit 2	Glacial diamicton (till); very sandy in eastern 2/3 of Sand River map area, less sandy in west
Unit 1	Clayey glacial diamicton (till), overlain by stratified sediment in some places
Muriel Lake Formation	Silt, sand, and gravel of glaciofluvial origin
Bronson Lake Formation	Clayey glacial diamicton (till) mixed with clay of undetermined origin
Empress Formation	Stratified sediment overlying bedrock and underlying lowermost glacial diamicton (till)
Unit 3	Stratified sand and gravel; contains clasts derived from Canadian Shield; glaciofluvial origin
Unit 2	Stratified silt and clay; fluvial or lacustrine origin
Unit 1	Stratified sand and gravel, mainly chert and quartzite derived from the Cordilleran Mountains; preglacial fluvial origin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Helina Valley
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Big Meadow Channel
Bronson Lake Channel
Holyoke Channel
Vermilion
Valley
St. Paul
Kikino
Valley
Beverly
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Sand and Gravel
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Unit Boundaries:
Approximate
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Contours, Interval 10 metres:
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Data Location
Talweg

Figure 8. Elevation of the upper surface of unit 1 of the Empress Formation. Note the distribution of unit 1, confined to the major buried preglacial valley bottoms.

gravel component is mainly light-colored quartzite with some dark chert, and local sandstone and ironstone. Softer rock such as limestone, dolostone, and local shale, sandstone, and siltstone, is not common within unit 1, indicating that only the harder, more distantly transported rock forms most of the gravel. Granitic and metamorphic clasts from the Canadian Shield are absent. The sand is predominantly light-colored quartz and dark-colored chert, which gives the deposit a salt-and-pepper appearance. The sand is generally medium-grained and the deposits are moderately well-sorted and compact. Commonly the sand is gray (5Y 5/2), indicating it is unoxidized, but in a few places it is pale olive (5Y 6/4).

Distribution, extent, and thickness

Figure 8 shows the distribution of the sand and gravel of unit 1 within the map area. Major deposits of unit 1 lie within the buried Helina, Beverly, and Kikino valley bottoms. The unit is not considered to lie on the interfluves between these valleys (figures 9 and 10, in pocket). The top of unit 1 in the map area ranges in elevation from as high as 550 m along the southern flank of the Beverly Valley, to as low as 455 m along the eastern segment of the Helina Valley (figure 8).

Within the Beverly Valley, unit 1 lies both on the floor of the valley and within terraces along the margins (figure 8). Unit 1 within the Helina Valley appears to be confined mainly to the valley floor. In the northwest segment of the Helina Valley, in Tp 67, R 13, the surface of the unit slopes to the northwest indicating that at one time drainage was in that direction. Farther east, however, in Tp 65, R 11, the surface of unit 1 slopes gradually to the northeast (figure 8), conforming to the slope of the underlying bedrock surface.

The surface of unit 1 in the Kikino Valley slopes to the northwest, indicating that the last stage of drainage in the valley was in that direction (figure 8). Near Bonnie Lake, in Tp 60, R 13, the lower stratigraphic sequence in the Kikino Valley shows evidence of glacially displaced sediment. In this area the lower sequence consists of a thin basal gravel overlain by a thin clay unit containing coal layers. That sequence, in turn, is overlain by a thick (thicker than 50 m), dense sand unit. Although this dense sand resembles the preglacial sand of unit 1, palynologic evidence (Singh, personal communication) indicates that this sequence of clay and sand is a displaced block from the Belly River Formation that probably was glacially thrust over unit 1 gravel (figure 10, cross section E4-E4').

Drill records from the Imperial Mills, Sinclair, and Vermilion valleys are sparse but do indicate that stratified sediment is present on the valley floors. Limited data indicate that this sediment consists mainly of unit 1 sand, with little or no gravel. Southwest of the map area, segments of the buried Vegreville Valley are known to contain unit 1 sand (Carlson 1967), but as much as 60 m of unit 3 glacial sand have also been mapped (Mougeot, in preparation). It is uncertain if unit 1 lies on the floor of the St. Paul Valley.

In general, deposits of unit 1 are about 10 m or less in thickness, though thicker deposits (thicker than 15 m) are mapped east of Vilna (Tp 59, R 12), near Owlseye (Tp 59, R 10), and near the confluence of the Beverly and Helina valleys in Tp 63, R 4 (figure 11). In these areas unit 1 consists primarily of medium-grained sand, overlying thin basal gravel.

Differentiation from other units

On the basis of differences in grain size, hardness, and resistivity responses (figure 12), sand and gravel of unit 1 are easily differentiated from the underlying claystone of the Lea Park Formation, and claystone and sandstone of the underlying Belly River Formation in the southwest corner of the map area. Problems in differentiation arise in those areas where unit 1 is composed essentially of sand and where it overlies soft sandstone of the Belly River Formation. The lithic composition of both units may be similar, and detailed petrologic or palynologic studies are necessary to differentiate these two units.

Where sand and gravel of unit 1 are overlain by clay of unit 2, the two are easily differentiated by the difference in grain size and electric-log responses. However, where sand and gravel of unit 1 are directly overlain by glacial sand and gravel of unit 3, the two units can be differentiated only by the presence or absence of granitic clasts from the Canadian Shield.

Nature of contacts

Lower contact

Unit 1 lies unconformably on the surface of the Lea Park and Belly River formations. Where unit 1 overlies claystone of either of these formations, the contact is easily recognized on the electric logs (figure 12). In those places where unit 1 is composed only of sand and where it overlies sandstone of the Belly River Formation, the contact may be difficult to recognize on the electric logs or from drill cuttings because of the similarity in grain size and lithic composition.

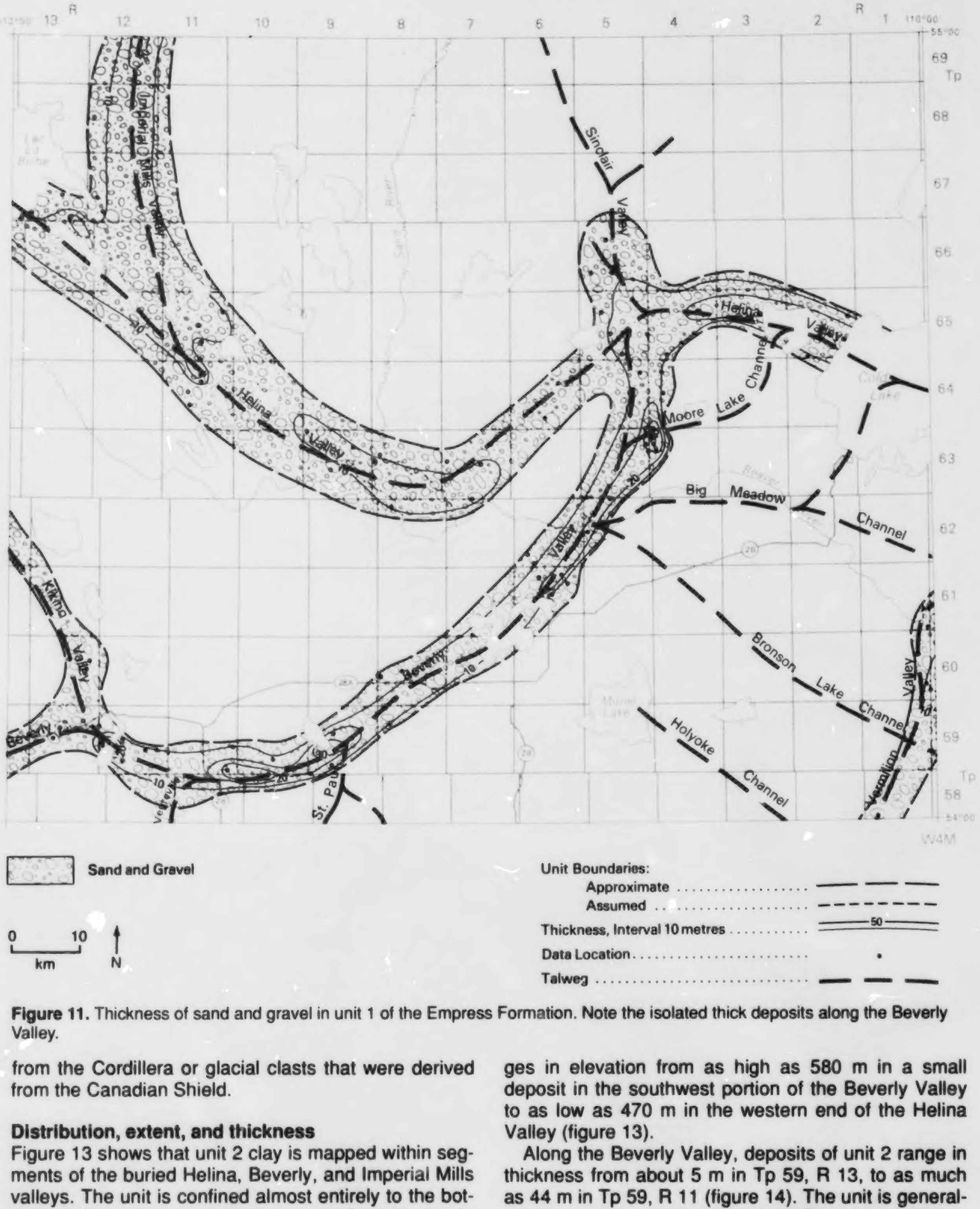
Upper contact

The upper contact of unit 1 with the overlying units differs from place to place. In segments of the major buried valleys the top of unit 1 is overlain by clay of unit 2 of the Empress Formation and the contact is easily recognized on the electric logs by the sharp decrease in resistivity of unit 2. In those places where clay of unit 2 is absent and where sand and gravel of unit 3 of the Empress Formation directly overlies unit 1, the contact cannot be easily defined, and can only be assumed on the basis of stratigraphic position and elevation of the top of unit 1 where it is recognized elsewhere nearby. In those places where both units 2 and 3 of the Empress Formation are absent, unit 1 is overlain by clay-rich diamicton and the contact is sharp and disconformable.

Unit 2: Silt and clay, minor sand and gravel

Description of unit

Unit 2 of the Empress Formation consists of dark gray silt and silty clay. Samples of the unit were not examined, but drill records describe the sediment as being laminated or finely bedded. In the northeast part of the study area between Tp 64-66, R 2-5 (figure 9, cross section E1-E1'), sand and gravel are commonly interbedded with the clay. It is uncertain whether all this gravel is composed of preglacial clasts derived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Moore Lake Channel
Big Meadow Channel
Beverly Valley
Kikino Valley
Beverly
Bronson Lake Channel
Holyoke Channel
Vermilion Valley
St. Paul
Vegreville
Cold Lake
Muriel Lake
Beaver River
10
20
30
Sand and Gravel
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10
km
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Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location
Talweg

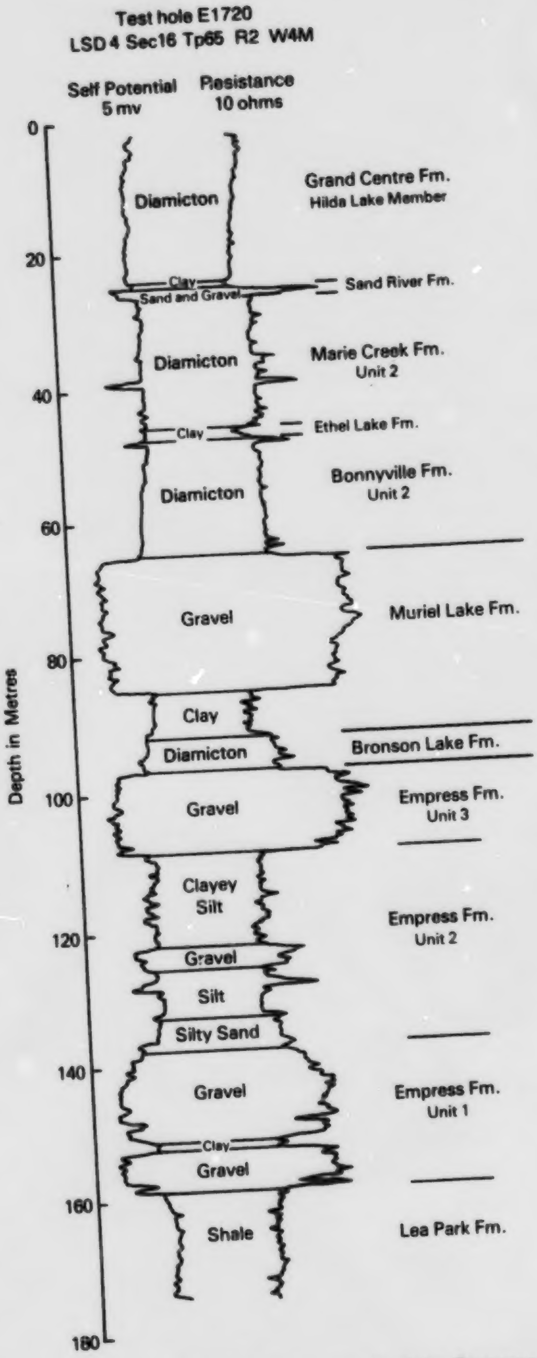
Figure 11. Thickness of sand and gravel in unit 1 of the Empress Formation. Note the isolated thick deposits along the Beverly Valley.

from the Cordillera or glacial clasts that were derived from the Canadian Shield.

Distribution, extent, and thickness

Figure 13 shows that unit 2 clay is mapped within segments of the buried Helina, Beverly, and Imperial Mills valleys. The unit is confined almost entirely to the bottoms of the valleys, except for two small areas, one in Tp 60, R 9 and one in Tp 65, R 13, where unit 2 deposits overlie bedrock flanks. The top of unit 2 ranges in elevation from as high as 580 m in a small deposit in the southwest portion of the Beverly Valley to as low as 470 m in the western end of the Helina Valley (figure 13).

Along the Beverly Valley, deposits of unit 2 range in thickness from about 5 m in Tp 59, R 13, to as much as 44 m in Tp 59, R 11 (figure 14). The unit is generally thick near the confluence of the Beverly and Helina valleys in Tp 64, R 5, where as much as 40 m of sediment lie within what appears to be a high-level terrace


Test hole E1720
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Hilda Lake Member
Sand River Fm.
Marie Creek Fm.
Unit 2
Ethel Lake Fm.
Bonnyville Fm.
Unit 2
Muriel Lake Fm.
Bronson Lake Fm.
Empress Fm.
Unit 3
Empress Fm.
Unit 2
Empress Fm.
Unit 1
Lea Park Fm.

Figure 12. Typical electric-log response of the Empress Formation.

(figure 9, cross section E2-E2', test hole E831; and figure 13). East of this confluence, unit 2 is extensive and generally thick within the Helina Valley, though it is locally composed of as much as 29 m of glaciofluvial sand and gravel interbedded with silt and clay (figure 9, cross section E1-E1'). To the west, small deposits ranging in thickness from 1 to 20 m lie along the south flank of the Helina Valley in Tp 65, R 12-13. Directly north of here, along the Imperial Mills Valley, unit 2 is extensive and about 10 m or less in thickness (figure 14).

Differentiation from other units

Unit 2 is most easily mapped in those areas where it overlies sand and gravel of unit 1 and in turn is overlain by sand and gravel of unit 3 of the Empress Formation. Unit 2 can be difficult to differentiate from soft, poorly lithified shale. Unit 2 silt and clay is differentiated from clayey deposits of younger formations, such as the Muriel Lake, Ethel Lake, and Sand River formations, primarily on the basis of stratigraphic position: unit 2 lies at or near the base of the stratigraphic sequence and is generally separated from the other clayey deposits by glacial diamicton.

Nature of contacts

Lower contact

The contact of unit 2 clay with unit 1 sand and gravel is discussed in the previous section. Adjacent to the Moore Lake Valley in Tp 64, R 3, clay of unit 2 directly overlies shale; this contact is difficult to recognize from either auger samples or electric-log responses.

Upper contact

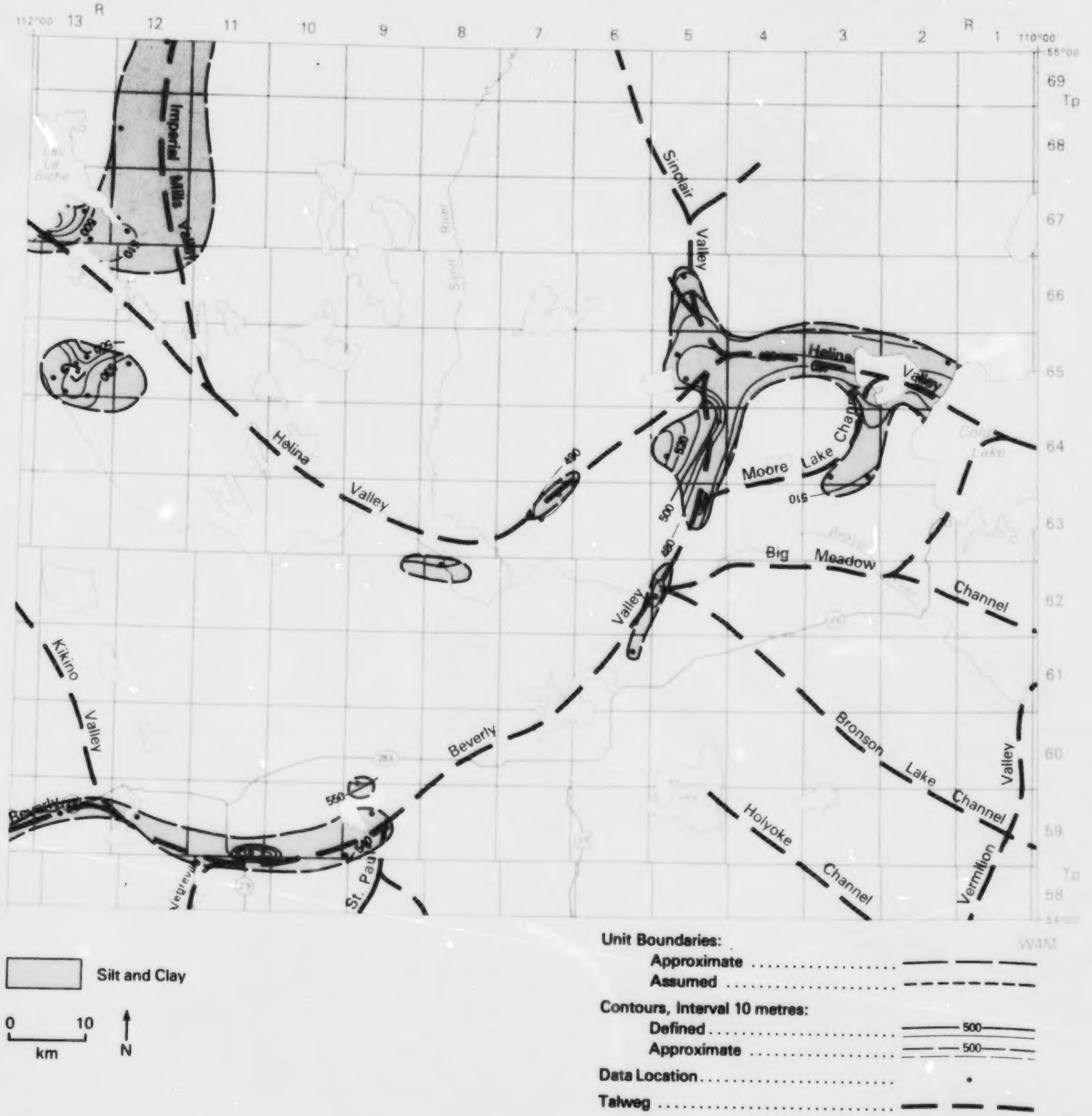
Unit 2 is overlain by sand and gravel of unit 3 in segments of the Helina, Beverly, and Imperial Mills valleys and this contact is generally sharp (figure 9, cross section E1-E1', test hole E765). In a few places where unit 2 is overlain by till, the contact is easy to recognize from descriptions of drill cuttings but may be poorly defined on the electric logs (figure 9, cross section E2-E2', test hole E457).

Unit 3: Glacial sand and gravel

Unit 3 of the Empress Formation consists mainly of sand and gravel that contains abundant igneous-rock and metamorphic-rock clasts derived from the Canadian Shield. The unit does not outcrop in the map area but is recognized from electric logs and is described as "glacial" gravel in the drillers' records, indicating that granitic clasts are present. The presence of these igneous and metamorphic rock clasts in the gravel indicates a glaciofluvial origin; hence, the term "glacial" is given to the unit, to differentiate it from preglacial gravel of unit 1. Locally small amounts of silt and clay are also present within the sand and gravel.

Description of unit

There is a paucity of lithologic information for unit 3 in the drill records. The sand is pinkish-brown where oxidized and pinkish-gray where unoxidized. The pink tinge is due to abundant potassium feldspar derived from granitic and metamorphic rocks. The size of the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Unit Boundaries:
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Contours, Interval 10 metres:
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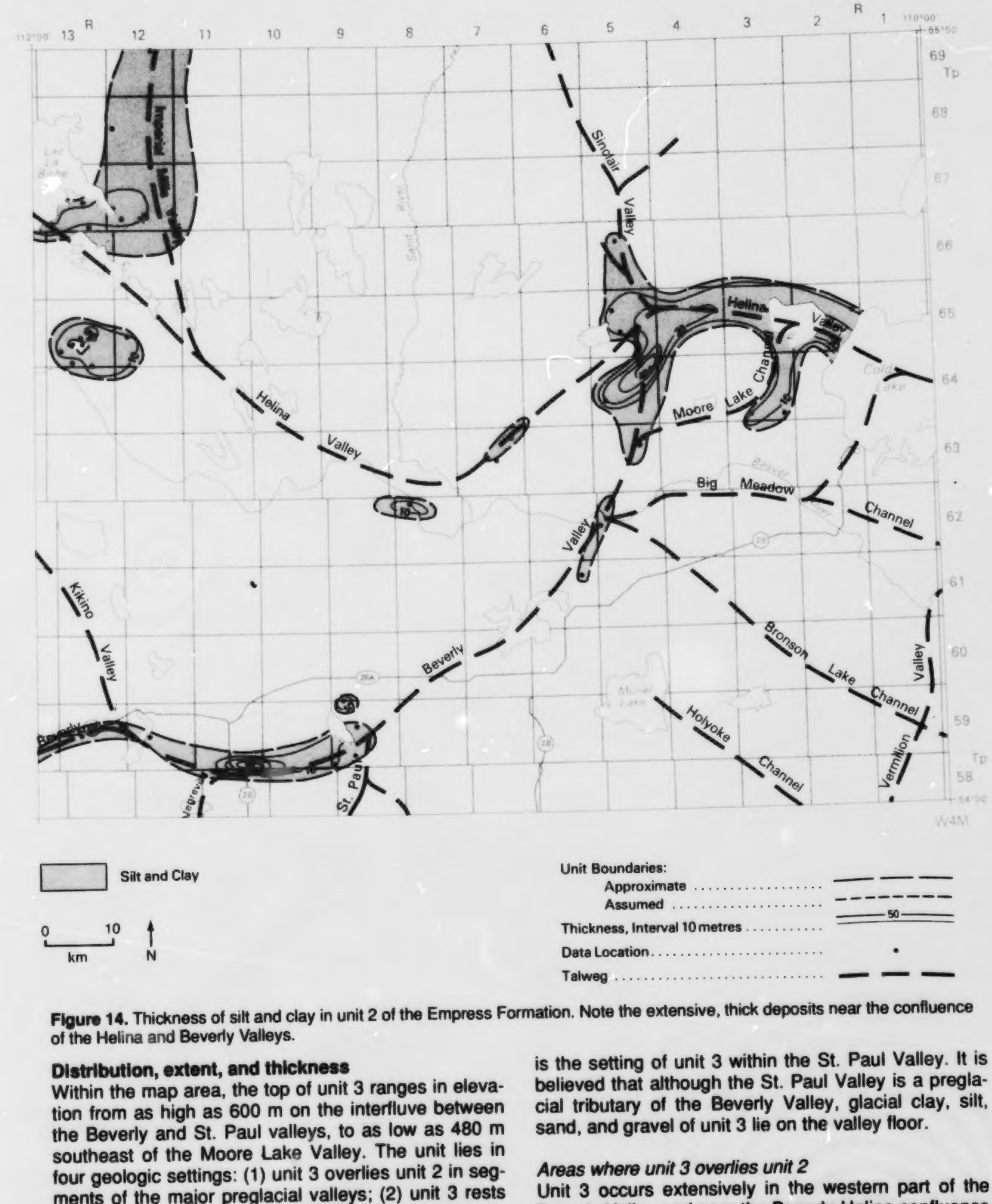
Figure 13. Elevation of the upper surface of unit 2 of the Empress Formation. Note the distribution of unit 2, confined to segments of the major preglacial valley bottoms.

sand is described in drillers' records as ranging from fine to coarse-grained and the deposits are generally soft and loose.

Unit 3 gravel is typically composed of stones transported into the area by glacial ice flowing from the northeast or by glacial meltwater. These include igneous and metamorphic rock derived from the Precambrian Canadian Shield, quartzose sandstone from the Cambrian Athabasca Formation, carbonate rock from the Devonian outcrops in Alberta and Saskatchewan, a small amount of quartzite and chert from the floors of the local preglacial valleys, and local Cretaceous sedimentary rock. The deposits are generally coarser and less well sorted than gravel of unit 1.

Within some of the buried channels in the east, unit 3 is described in the field log descriptions as being composed of preglacial-type gravel consisting of quartzite and chert. The authors consider this preglacial sediment to have been eroded from the floors of the preglacial valleys by glacial meltwater, and deposited within the buried glacial channels.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Vermilion Valley
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Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
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Data Location
Talweg

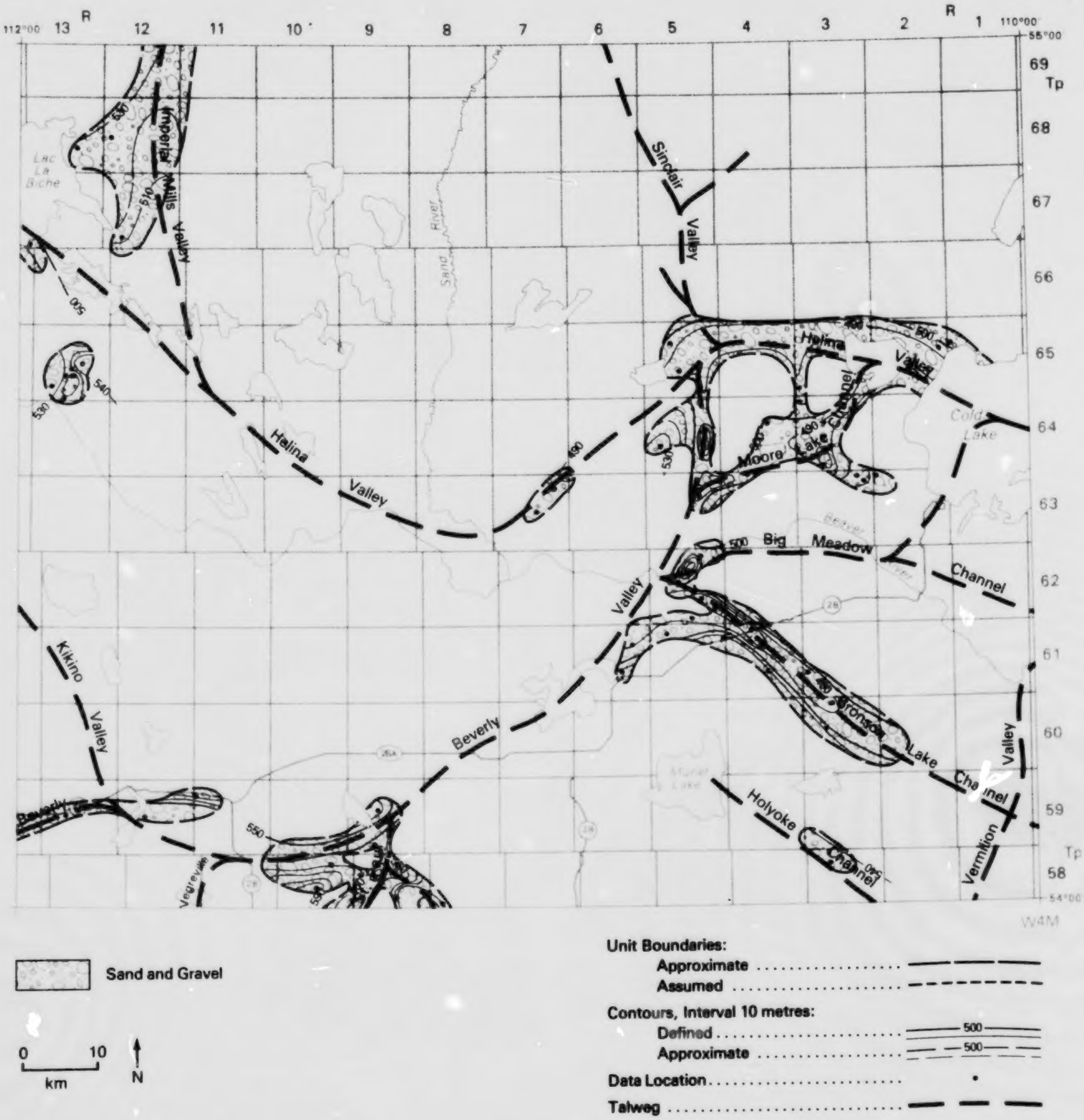
Figure 14. Thickness of silt and clay in unit 2 of the Empress Formation. Note the extensive, thick deposits near the confluence of the Helina and Beverly Valleys.

Distribution, extent, and thickness

Within the map area, the top of unit 3 ranges in elevation from as high as 600 m on the interfluve between the Beverly and St. Paul valleys, to as low as 480 m southeast of the Moore Lake Valley. The unit lies in four geologic settings: (1) unit 3 overlies unit 2 in segments of the major preglacial valleys; (2) unit 3 rests on the floors of a number of major buried glacial channels; (3) unit 3 rests on the level bedrock surface adjacent to these buried channels; and (4) a special case is the setting of unit 3 within the St. Paul Valley. It is believed that although the St. Paul Valley is a preglacial tributary of the Beverly Valley, glacial clay, silt, sand, and gravel of unit 3 lie on the valley floor.

Areas where unit 3 overlies unit 2

Unit 3 occurs extensively in the western part of the Beverly Valley and near the Beverly-Helina confluence in Tp 65, R 5 (figure 15). It may also be present in the central segment but is not shown, either because data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Sand River
Sinclair Valley
Helina Valley
Moore Lake Channel
Cold Lake
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Bronson Lake Channel
Kikino Valley
Muriel Lake
Holyoke Channel
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Vegreville
Sand and Gravel
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Unit Boundaries:
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Contours, Interval 10 metres:
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Data Location
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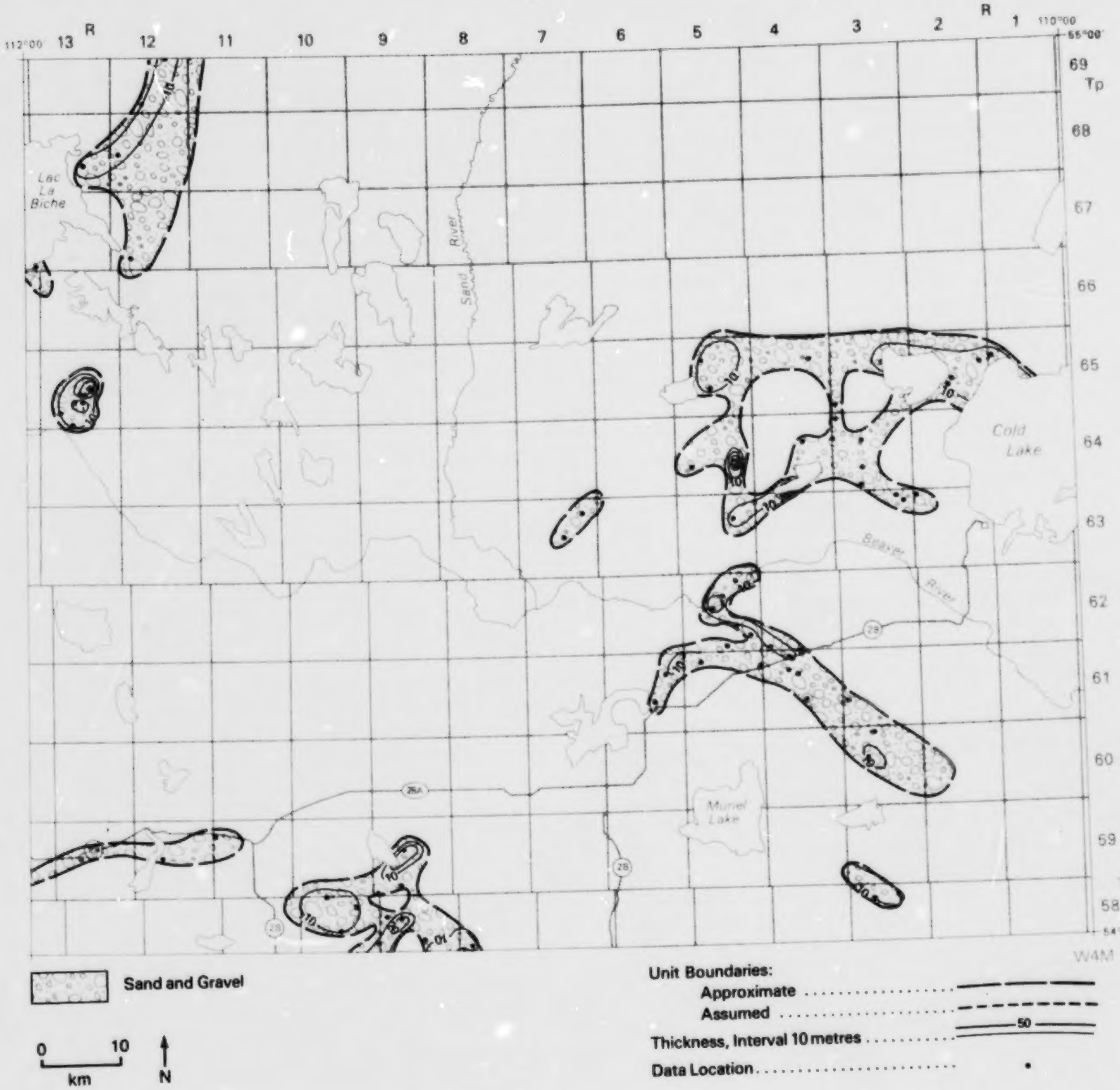
Figure 15. Elevation of the upper surface of unit 3 of the Empress Formation. Note the distribution of unit 3, confined to segments of the buried preglacial valleys and glacial channels.

are lacking or because unit 2 clay is absent, making it difficult to differentiate unit 3 from the underlying unit 1. Similarly, unit 3 is absent or discontinuous in the central and western part of the Helina Valley, but is extensive east of the Beverly-Helina confluence in Tp 65, R 5 (figure 15). Although extensive deposits of unit 3 are shown throughout most of the Imperial Mills Valley (figure 10, cross section E4-E4'; and figure 15), there is doubt as to whether or not the sediments should in fact be grouped within the stratigraphically higher Muriel Lake Formation. The deposits fall into the broad stratigraphic definition of unit 3, but their elevation is similar to that of the stratified deposits of the Muriel Lake Formation in the western part of the Helina Valley (figure 9, cross section E3-E3'; and figure 10, cross section E4-E4').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Beaver River
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Unit Boundaries:
Approximate
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Thickness, Interval 10 metres
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Data Location

Figure 16. Thickness of sand and gravel in unit 3 of the Empress Formation.

The thickness of unit 3 in these buried preglacial valleys ranges from a few metres in the Imperial Mills Valley to as much as 44 m in Tp 64, R 5 near the confluence with the Helina Valley (figure 9, cross section E2-E2', test hole E803; and figure 16).

Unit 3 on the floors of buried glacial channels

Unit 3 lies on the floors of segments of the buried Moore Lake, Big Meadow, Bronson Lake and Holyoke channels, as well as within a small, unnamed channel that cuts through the interfluve between the Helina Valley and Moore Lake Channel in Tp 64-65, R 3-4. The unit has a sporadic distribution within the Moore Lake Channel, possibly due to fluvial erosion (figure 15). Evidence of erosion is shown in test hole E762, near Ethel Lake in Tp 64, R 3, where a thick sequence of younger silt and clay fills a narrow channel that was cut through all preexisting deposits and into bedrock (figure 9, cross section E1-E1').

Within the Big Meadow Channel, unit 3 can be mapped with certainty only in the western segment, where the overlying diamicton of the Bronson Lake Formation separates unit 3 from stratified deposits of the stratigraphically higher Muriel Lake Formation. Along the central and eastern parts of the valley the Bronson Lake Formation is absent; here, the stratified deposits on the valley floor are included within the younger Muriel Lake Formation even though sand and gravel of unit 3 may lie at the base.

Unit 3 lies extensively within the central and western parts of the Bronson Lake Channel (figure 15). It probably extends into the eastern segment of the channel, though it is not shown because information is lacking in that area. The surface of unit 3 appears to slope gently westward from Tp 60, R 3 toward the junction of the Bronson Lake Channel and Beverly Valley in Tp 62, R 5. Drill records from the western ends of both the Big Meadow and Bronson Lake channels describe the composition of the gravel as predominantly chert and quartzite. The source of this is likely preglacial sediment of unit 1 that was eroded from the Beverly Valley and deposited in the glacial channels.

The thickness of unit 3 in the buried glacial channels ranges from about 5 m along the edges, to as much as 19 m along the talwegs (figure 16). Extremely thick deposits of unit 3 lie in the western end of the Moore Lake Channel where about 78 m of clay, sand and gravel apparently fill in a deeply-eroded part of the channel (figure 10, cross section N2-N2', test hole E774). The thick (29 m) deposits of sand and gravel in the southwest corner of Tp 62, R 5 are mapped as unit 3 but may possibly contain deposits of the stratigraphically higher Muriel Lake or Ethel Lake formations that are superimposed on top of unit 3.

Unit 3 on the bedrock interfluves

Unit 3 is found within a few small areas on top of the level bedrock surface adjacent to buried valleys and channels. These areas include the following: the interfluve between the Beverly Valley and the west branch of the St. Paul Valley in Tp 58, R 10; southeast of the Moore Lake Channel in Tp 63-64, R 2-3; and a poorly defined channel in Tp 65, R 13 (figure 15). The thickness of the unit on these interfluves is generally less than 10 m, though locally may be as much as 45 m (figure 16, Tp 65, R 13).

Unit 3 in the St. Paul Valley

The deposits within the St. Paul Valley are interpreted to be unit 3 on the basis of stratigraphic position; they rest on bedrock in the valley floor, they are higher in elevation than unit 1 within the Beverly Valley to the north, and they can be correlated, on the basis of elevation, with unit 3 deposits that overlie unit 2 clay within the Beverly Valley to the north. Drill records show that the unit appears to be discontinuous within the valley and that it contains significant amounts of clay as well as sand and gravel. The thickness of unit 3 in both branches of the valley ranges from 3 to 24 m (figure 16).

Differentiation from other units

Unit 3 is most easily recognized in those areas where it overlies clay of unit 2 and in turn is overlain by glacial diamicton. This stratigraphic setting is found only within segments of the buried preglacial Beverly, Helina, and Imperial Mills valleys (figures 13 and 15). Unit 3 is also easy to map in the buried glacial channels where it lies on the bedrock surface and is overlain by diamicton of the Bronson Lake Formation. Unit 3 can be difficult to differentiate from younger sand and gravel deposits of the Muriel Lake Formation if the two are in contact. An example of this is in the eastern segment of the Bronson Lake Channel in the map area (figure 9, cross section E1-E1').

Nature of contacts

Lower contact

Sharp lower contacts are evident where unit 3 sand and gravel lie either on the bedrock surface within and adjacent to some of the buried glacial meltwater channels, or on top of clay of unit 2. This contact is easily recognized on the resistivity-log responses (figure 12).

Upper contact

Unit 3 has a sharp contact with overlying deposits of diamicton, as shown by the sharp decrease in resistivity of the diamicton (figure 9, cross section E2-E2', test hole E1712). Due to the similarities in composition and electric-log responses, the contact cannot be easily defined where unit 3 is directly overlain by younger glaciofluvial sand and gravel deposits.

Origin of the sediment in the Empress Formation

Within the major preglacial valleys, unit 1 of the Empress Formation consists of sediment deposited by rivers flowing northeast from the Cordillera. Evidence to support this is the distribution of the unit along the floors of the large valleys west of the map area and the clast composition that consists primarily of quartzite and chert from the Cordillera and from Tertiary gravel that once capped the uplands flanking the major river systems. The sand of unit 1 probably had more than one source. Some of the sand probably was derived from the Cordillera along with the gravel. The bulk of the sand, however, probably was derived from the soft Cretaceous sandstone that lies within and west of the map area. The predominance of sand on the floors of the tributary valleys, which had their headwaters in the plains region, also indicates a source from the underlying bedrock.

Silt and clay deposits of unit 2 are interpreted to be either overbank sediment deposited by rivers in the preglacial valleys or offshore sediment deposited in lakes formed by the blockage of the valleys by glacial ice. There is no direct evidence to support either hypothesis, although the silt and clay are described as laminated to finely bedded, which favors an offshore lake origin. Furthermore, the wide distribution of unit 2 in the Imperial Mills Valley supports the hypothesis of an extensive glacial lake that flooded the entire valley. The preservation of the fine deposits in this valley can be attributed to the protective mantle provided by the overlying sand and gravel (figure 10, cross section E4-E4'). Elsewhere, particularly within the Helina and Beverly valleys, unit 2 has a sporadic distribution. This is attributed to a number of possible causes: the first glacier in the area, the Cherry Grove Glacier, may have eroded the silt and clay as it advanced over the valleys, and this incorporated material was later deposited as clayey till, with inclusions of bedded clay, of the Bronson Lake Formation. Another possibility is that silt and clay of unit 2 were deposited contemporaneously with till of the Bronson Lake Formation, during the early phases of the Cherry Grove Glaciation, and cannot be differentiated as a discrete unit from test hole information. A third reason for the discontinuous distribution of unit 2 is fluvial erosion by glacial meltwater flowing off the advancing margin of the Cherry Grove Glacier.

The sediment of unit 3 of the Empress Formation is probably glaciofluvial sediment, though this is not certain. Evidence to support a glaciofluvial origin is the granitic composition of the clasts, which indicates they were derived from the Canadian Shield. A fluvial origin, rather than onshore lake origin, is preferred mainly because most of the unit is confined to floors of well-defined channels on the bedrock surface or overtop older stratified deposits in segments of the major preglacial valleys.

The widespread sand and gravel deposits of unit 3 that overlie unit 2 along the eastern part of the Helina Valley, as well as within the Imperial Mills Valley and parts of the Beverly Valley, are interpreted to be meltwater stream sediment that preceded the Cherry Grove Glaciation during the southwestward advance. The evidence for this is mainly stratigraphic; unit 3 is buried by, and therefore must have been deposited prior to, the Bronson Lake till. The thick deposits of unit 3 within the western end of the Moore Lake Channel (as much as 78 m) and within the Beverly Valley in Tp 59, R 9-10 are interpreted to have been deposited by glacial meltwater flowing from a nearby glacier. The overdeepening of the western end of the Moore Lake Channel (figure 10, cross section N2-N2', test hole E774) possibly resulted from meltwater flowing off a steep ice front. This overdeepening was apparently confined to the western segment of the channel because farther east the channel floor rises steeply, indicating less erosion. Other evidence to suggest the presence of an ice margin along the channel is that in Tp 64, R 5, the elevation of unit 3 is considerably higher and the deposits are much thicker than surrounding deposits of unit 3 (figures 15 and 16). This suggests that unit 3 was deposited in contact with ice, possibly as a collapse hummock. A collapse hummock is also indicated in Tp 59, R 9-10 by the thick sequence of sand and gravel that lies at an elevation higher than the surrounding deposits in the Beverly Valley (figure 15). Presumably, meltwater in this area flowed off the glacier margin and drained southwest along the west channel of the St. Paul Valley. This is supported by the southwest slope of the surface of unit 3 in the St. Paul Valley, that indicates flow in that direction at one time.

Bronson Lake Formation

Source of name: Bronson Lake, Saskatchewan, located in the Waterhen map area, NTS 73K.
Type section: Alberta Environment rotary test hole E802, located in LSD 5, Sec 32, Tp 61, R 5, W 4 Mer in the Sand River map area, NTS 73L (figure 17).
Type area: The area around Fort Kent and southeast to Angling Lake in the southeast corner of the Sand River map area, NTS 73L.
Reference sections: Alberta Environment rotary test holes E1708 (LSD 4, Sec 14, Tp 62, R 5, W 4 Mer), and E1712 (LSD 1, Sec 11, Tp 62, R 5, W 4 Mer); Alberta Geological Survey auger test hole T32 (LSD 12, Sec 1, Tp 64, R 3, W 4 Mer).

Description of unit

The Bronson Lake Formation does not outcrop within the map area but is mapped from auger and rotary-drill cuttings, electric logs and drillers' records. The formation contains a nearly clast-free, clayey diamicton that in places contains, or is interbedded with, well-sorted sediment, predominantly clay of undetermined origin (table 2). One such area is along the Helina Valley, west of Cold Lake in Tp 65, R 2, where the formation consists of both clay and diamicton (figure 9, cross section E2-E2', test hole E831). In most places the formation has very low resistivity, presumably the result of abundant clay. The formation is easily recognized using the electric logs where it is both overlain and underlain by sand and gravel (figure 9, cross section E2-E2', test holes E1708 and E1712; and figure 17). The resistivity of the unit is almost as low as that of the marine claystone of the underlying Lea Park Formation.

In this study the Bronson Lake Formation was recognized in only one auger hole (Andriashek and Fenton 1979, test hole T32), in which it was dark gray brown (2.5Y 4/2). In most places however, the formation is unoxidized and is dark gray, as described in the Alberta Environment drill logs. In test hole T32, the smaller-than-2-mm fraction of the diamicton is composed of about 24% sand, 33% silt, and 44% clay (figure 18). The very-coarse-sand fraction contains about 35% igneous and metamorphic rock, 42% quartz, 3% limestone, 3% dolostone, and 14% local rock, mainly claystone. The silt-clay fraction contains about 9% calcareous material (calcite/dolomite ratio = 0.34).

Gold's (1978) data show that there is more aluminum in the diamicton of the Bronson Lake Formation than in the diamictons of the other formations. This probably is due to the abundance of clay in the diamicton.

Distribution, thickness, and subcrop topography

The Bronson Lake Formation lies primarily within or along segments of the major buried valleys and channels (figure 19). It has not been identified in the interfluves, except for the areas between the Bronson Lake and Holyoke channels in the southeast and between the Beverly and St. Paul valleys in the southwest.

The Bronson Lake Formation lies within much of the Helina Valley in the map area. It is uncertain if the formation extends throughout the valley, but it is continuous or nearly continuous in the central and eastern part of the valley, extending from Tp 65, R 2 in the east, to Tp 65, R 11 in the west (figure 19).

Oil-company electric logs from test holes located above the Vermilion Valley show that coarse deposits of the Empress Formation are overlain by clay that, on the basis of elevation and stratigraphic position, correlates with the Bronson Lake Formation in the Bronson Lake Channel to the west (figure 10, cross section N1-N1'). The Bronson Lake Formation is widespread within the western part of the Bronson Lake Channel between Tp 61, R 3 and Tp 62, R 5 and on the bedrock between the Holyoke Channel to the south. The formation probably was eroded from the central and eastern segments of the Bronson Lake Channel, although the data are sparse in this area.

Within the map area the top of the formation ranges in elevation from as high as 550 m along the southwest part of the Beverly Valley to as low as 490 m in the Bronson Lake Channel and the eastern part of the Beverly Valley (figure 19). On average, the thickness of the formation is about 10 m or less (figure 20). The unit is thickest in the central segment of the Helina Valley (28 m), the western end of the Bronson Lake Channel, and parts of the Vermilion Valley (22 m).

Differentiation from other units

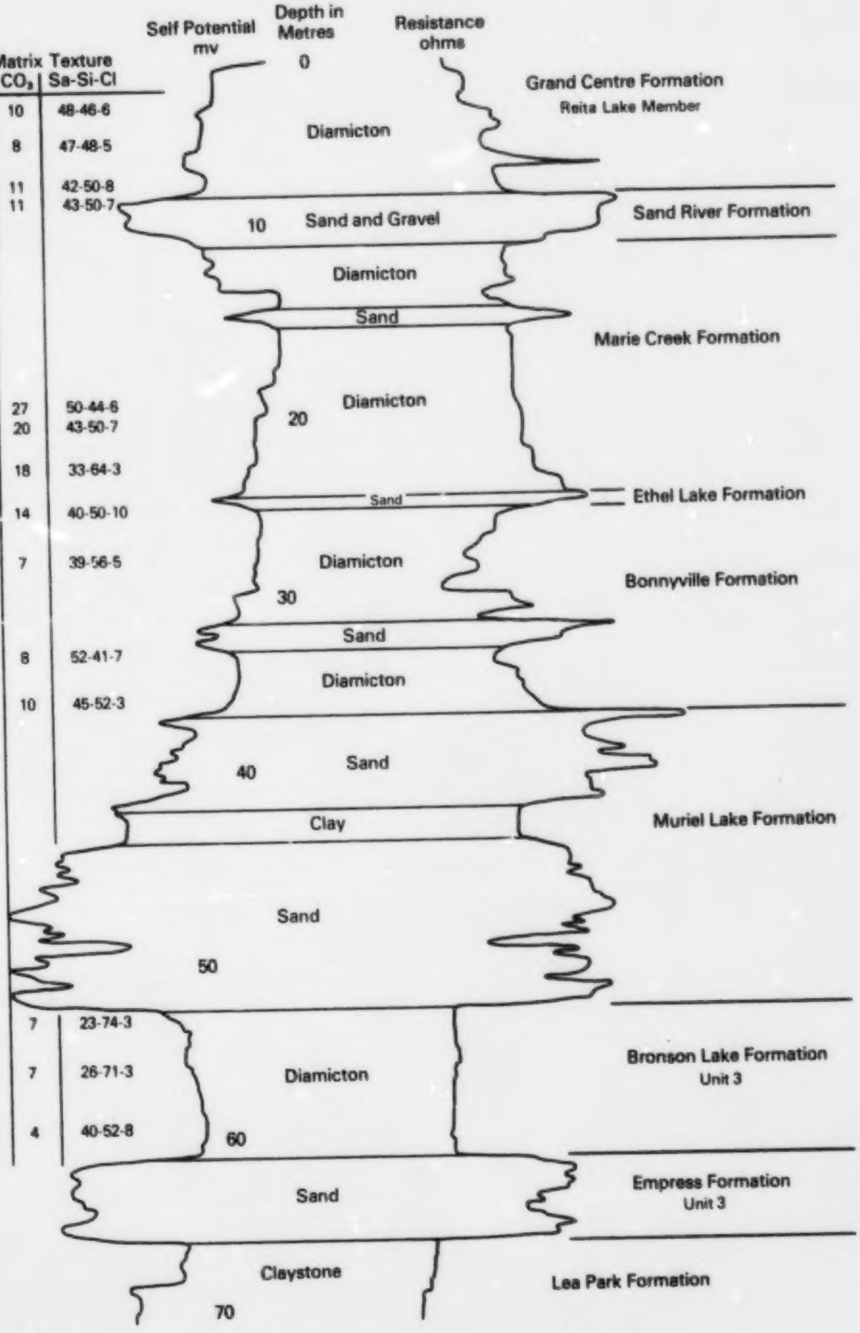
The Bronson Lake Formation is most easily mapped where it overlies coarse deposits of the Empress Formation and where it is overlain by coarse deposits of the Muriel Lake Formation (figure 9, cross section E2-E2', test holes E1708 and E1712). In places the Bronson Lake Formation is difficult to differentiate from clay of unit 2 of the Empress Formation because locally the formation consists of diamicton interbedded with bedded silt and clay or massive clay (figure 9, cross section E2-E2', test hole E831). Differentiation between these two units is particularly difficult in the area west of Cold Lake and Marie Lake (Tp 65, R 2) where clayey sediment lies above and below a clay-rich and nearly clast-free diamicton.

In the southwest part of the map area the distri- bution and extent of the formation are uncertain, primarily because only electric logs are available. A number of oil-company electric logs in Tp 58-59, R 12 show that a clayey unit overlies the Empress Formation, and, on the basis of stratigraphic position, this unit is

Test hole E802 LSD5 Sec32 Tp61 R5 W4M

• Sample Depth (metres)	(feet)	Ign.-Meta	Qtz.	CO_3	Local	Matrix CO_3	Texture Sa-Si-Cl
3.0	10	75	23	0	2	10	48-46-6
4.5	15	78	19	2	2	8	47-48-5
6.7	22	83	13	2	3	11	42-50-8
7.6	25	80	16	1	3	11	43-50-7
19.8	65	88	8	5	1	27	50-44-6
20.4	67	79	17	4	1	20	43-50-7
22.8	75	72	24	4	1	18	33-64-3
25.9	85	61	33	2	3	14	40-50-10
28.9	95	71	24	1	5	7	39-56-5
33.5	110	65	32	1	3	8	52-41-7
33.0	115	65	27	6	3	10	45-52-3
53.3	175	36	27	4	35	7	23-74-3
56.3	185	48	23	2	28	7	26-71-3
59.4	195	33	16	3	48	4	40-52-8

*(Data from Gold, 1978)

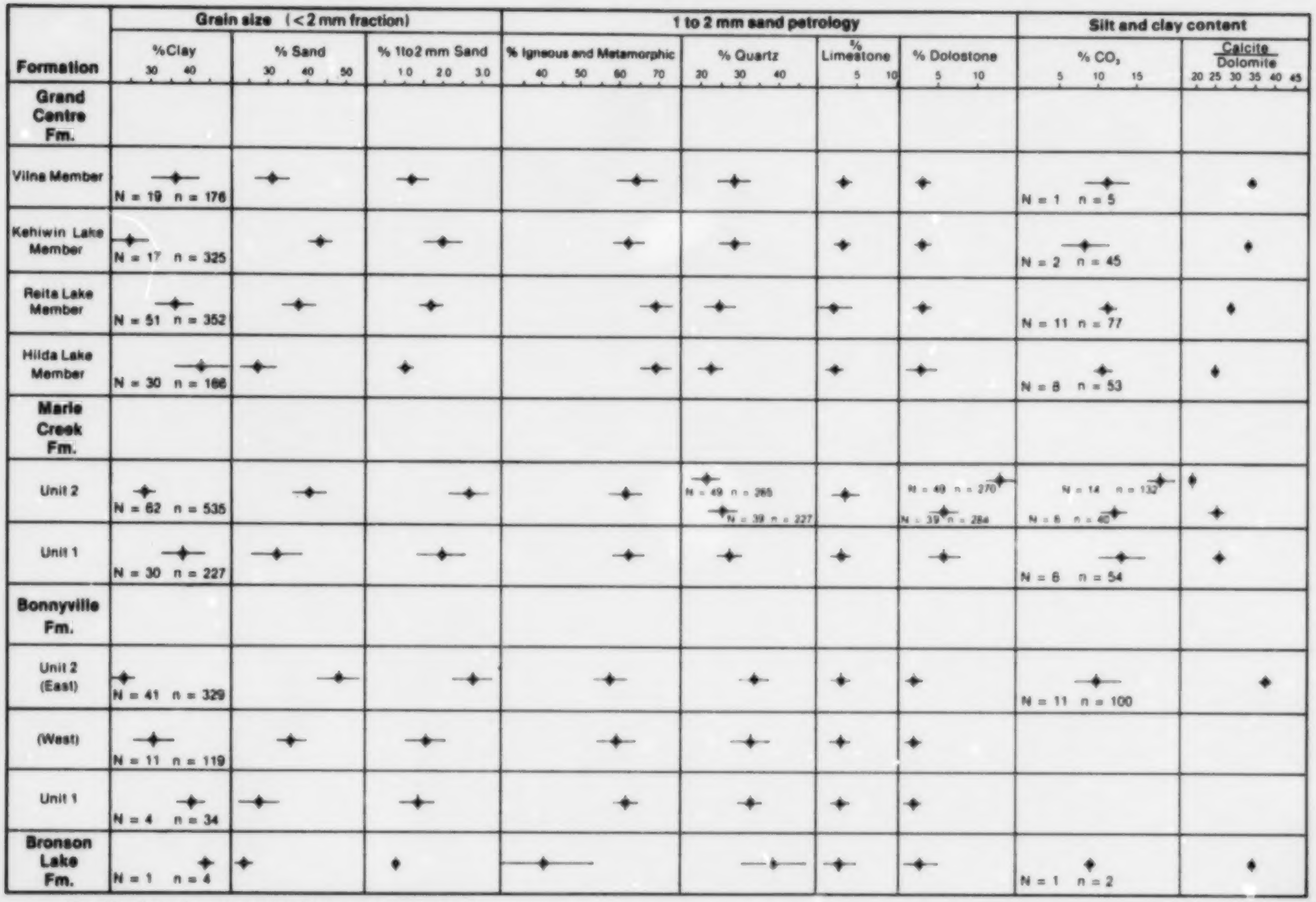


Ign-Metm - % Igneous and Metamorphic rock
Qtz - % Quartz
Carb - % Carbonates
Local - % Local rock

CO_3 - % Carbonate content of silt and clay fraction

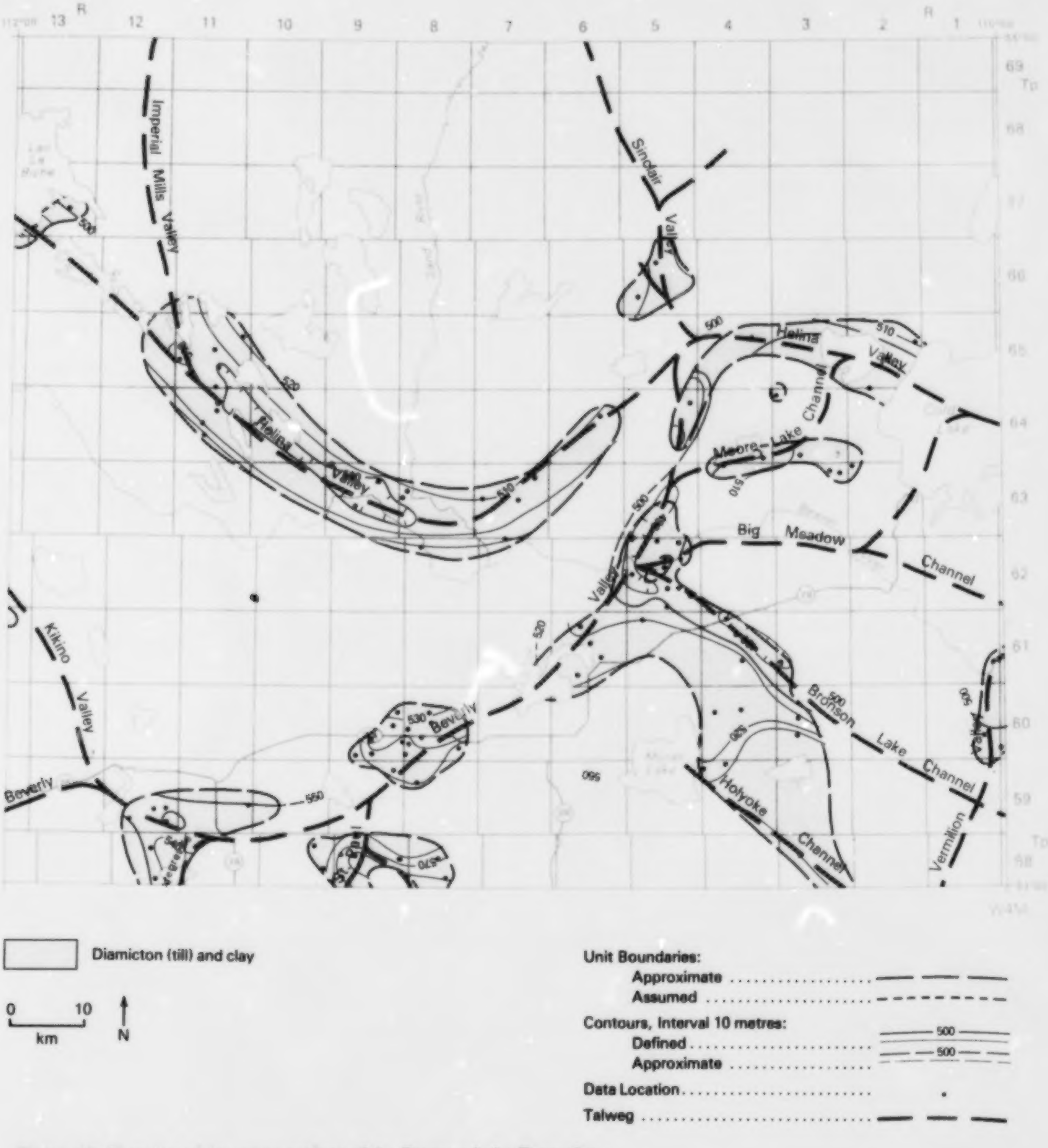
Sa - % Sand
Si - % Silt
Cl - % Clay

Figure 17. Electric log of the type section of the Bronson Lake Formation and Muriel Lake Formation. Alberta Environment test hole E802.



N = Number of test holes in which unit is recognized
n = Number of samples analyzed from test holes
♦ Mean value of the means from all test holes
— Standard deviation

Figure 18. Properties that characterize the tills of glacial formations in the Sand River map area.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6
5
4
3
2
R
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64
63
62
61
60
59
Tp
58
W4M
Imperial Mills Valley
Sinclair Valley
Helina Valley
Helina Valley
Moore Lake Channel
Big Meadow Channel
Valley
Kikino Valley
Beverly
Beverly
Bronson Lake Channel
Holyoke Channel
Vermilion
500
510
520
530
540
550
560
570
Diamicton (till) and clay
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Contours, Interval 10 metres:
Defined
Approximate
500
Data Location
Talweg

Figure 19. Elevation of the upper surface of the Bronson Lake Formation.

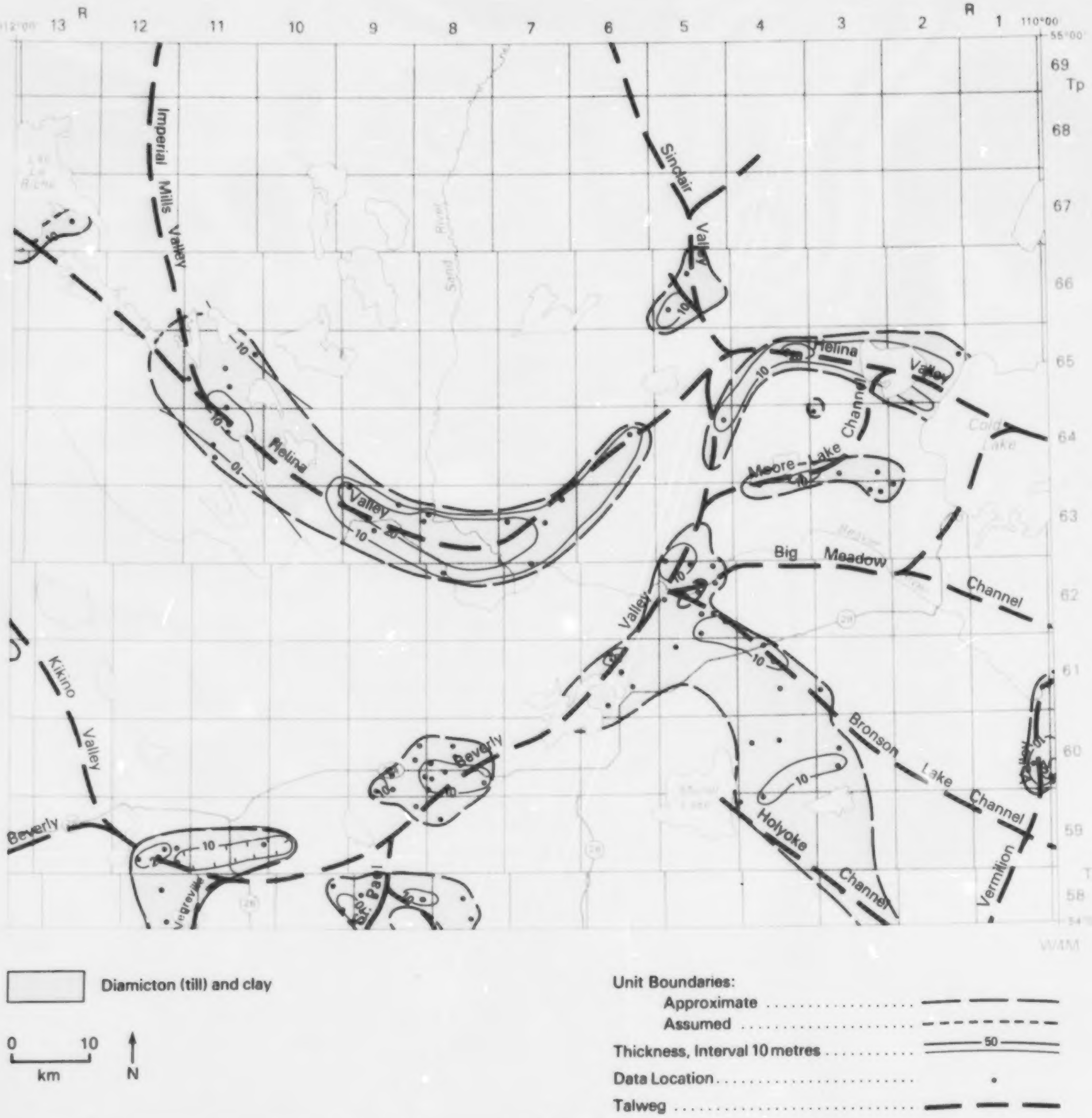
interpreted to be the Bronson Lake Formation. However, the clayey unit 1 of the overlying Bonnyville Formation is also present in the area and could be miscorrelated with the Bronson Lake Formation. In the east, these two units are commonly separated by sand and gravel of the Muriel Lake Formation and their differentiation is not difficult.

In some areas where unit 2 of the Bonnyville Formation directly overlies the Bronson Lake Formation, the differentiation is made on the basis of the very sandy texture of the diamicton and the lesser amount of local rock fragments in the very-coarse-sand fraction of the Bonnyville Formation.

Nature of contacts

Lower contact

The Bronson Lake Formation overlies claystone of the Lea Park Formation in a few places within the uplands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Imperial Mills Valley
Sinclair Valley
Helina Valley
Helina Valley
Channel
Moore Lake
Big Meadow Channel
Valley
Kikino Valley
Beverly
Beverly
Bronson Lake Channel
Holyoke Channel
Vermilion
Vegreville
St. Paul
Cold Lake
Sand River
10
20
W.M.
Diamicton (till) and clay
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location
Talweg

Figure 20. Thickness of diamicton and clay in the Bronson Lake Formation.

flanking the buried valleys and channels. This contact is disconformable and generally sharp, even though both formations contain abundant clay (figure 10, cross section N1-N1', test holes E801, E716, and E719). Gradational contacts between the two units are evident in test hole E799 (figure 10, cross section N1-N1') in which diamicton of the Bronson Lake Formation becomes progressively more clayey near the bedrock surface. A number of drillers' records describe blocks of "ice-rafted shale" within the diamicton of the Bronson Lake Formation, which indicates that in places a significant amount of the underlying bedrock has been eroded and incorporated into the formation.

In most places the Bronson Lake Formation overlies the Empress Formation, and where the latter consists of sand and gravel, the contact is sharp (figure 9, cross section E2-E2', test holes E1708 and E1712; and figure 10, cross section N2-N2', test hole E1723). Gradational contacts with the Empress Formation are shown in test hole E807 (figure 9, cross section E3-

E3') where the underlying sand and gravel have been incorporated into the base of the Bronson Lake Formation. It is believed that the Bronson Lake Formation directly overlies clay of unit 2 of the Empress Formation in a few areas in the northeastern part of the map area. Here, it can be difficult to establish the contact between the two units because both contain considerable amounts of clay. For example, in test hole E831 (figure 9, cross section E2-E2'), drillers' records describe "till"; this is interpreted to be the Bronson Lake Formation, even though the electric logs show no difference between the so-called till and the underlying clay of unit 2.

Upper contact

The contact between the Bronson Lake Formation and stratified deposits of the overlying Muriel Lake Formation is interpreted to be conformable and, in most places, is distinct and well defined on the electric logs (figure 17). Where the base of the Muriel Lake Formation consists of silt and clay, the contact with the Bronson Lake Formation is not as sharp (figure 12).

Origin and differences in the properties of the sediment in the Bronson Lake Formation

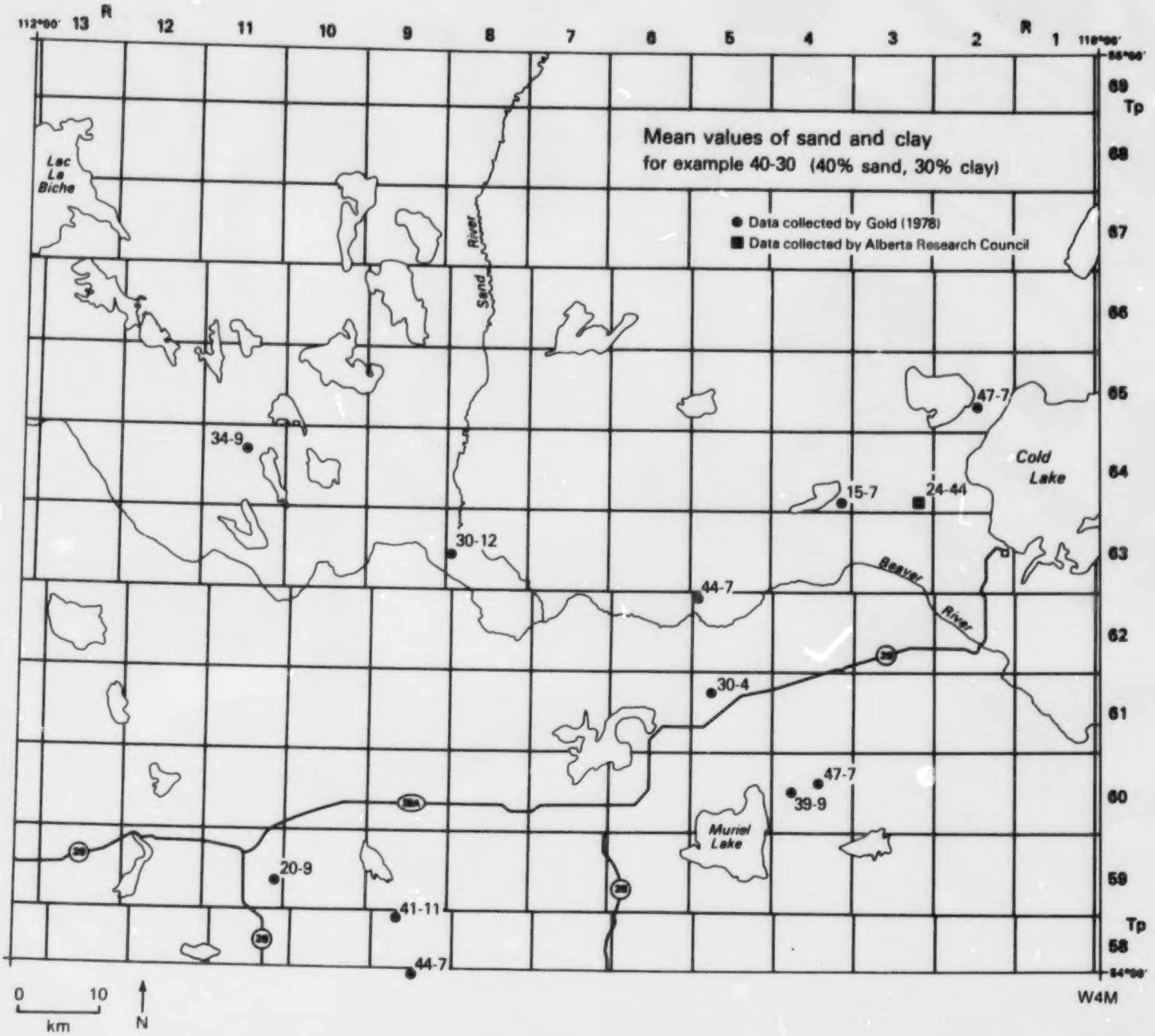
The Bronson Lake Formation comprises sediment deposited during the Cherry Grove Glaciation. Much of the formation is composed of diamicton that is interpreted to be till. However, because the formation is found at or near the base of major buried valleys and channels, some of the formation may include diamicton derived from sediment slumped from the valley walls.

Local differences in the grain size of the diamicton in the Bronson Lake Formation are evident. Gold's (1978) data show that although the diamicton is generally very silty to clayey, in places it is also sandy (figure 21, test holes E765, E458, E801, and E719). Glacial erosion and incorporation of the underlying sand and gravel of the Empress Formation is one explanation of this variance in grain size.

Within the Helina Valley, the diamicton of the Bronson Lake Formation is very clayey and contains discrete masses or beds of silt and clay. The source of this silt and clay is uncertain. Gold's (1978) very-coarse-sand data show that in places the diamicton contains abundant local rock fragments consisting mainly of claystone. This agrees with the data from test hole T32 (figure 18), which also show abundant claystone, as much as 14%, in the very-coarse-sand fraction. This abundant claystone, compared to the amount in other formations, indicates that the underlying Lea Park Formation was eroded and large amounts were incorporated into the Bronson Lake Formation. Other evidence for bedrock incorporation is recorded in the drillers' log descriptions along the Helina Valley in the northeast corner of the map area. These logs describe clay deposits, composed of "ice-rafted shale", that overlie till, interpreted to be the Bronson Lake Formation. Christiansen (1968) also noted an abundance of clay and abundance of shale in the clast fraction of the lowermost till in a number of map areas of Saskatchewan. He too attributed this enrichment of clay to the erosion and incorporation of extensive areas of exposed bedrock by early glaciations in that area.

Although incorporation of claystone likely accounts for some of the clay masses and the clayey composition of the Bronson Lake Formation, at a number of locations fluvial or lacustrine silt and clay has either been deposited penecontemporaneously with the till or glacially incorporated and later deposited as clasts in the till. The source of the incorporated silt and clay may be the underlying unit 2 of the Empress Formation, which is considered to have been deposited in a proglacial environment during the advance phase of the Cherry Grove Glaciation. Possibly glacial erosion accounts for the absence of unit 2 in segments of the buried valleys and channels. It is equally possible that lacustrine sediment of unit 2 and till of the Bronson Lake Formation were deposited contemporaneously with the advance phase of the Cherry Grove Glaciation.

The absence of the Bronson Lake Formation in the eastern part of the Bronson Lake Channel and within most of the Big Meadow Channel is attributed to fluvial erosion that occurred during the retreat of the Cherry Grove ice margin. Glacial meltwater eroded the Bronson Lake till within the valley and deposited thick sand and gravel on top of sand and gravel of unit 3 of the Empress Formation. This deposition resulted in a thicker than normal sequence of sand and gravel at the bases of both of these channels.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Mean values of sand and clay
for example 40-30 (40% sand, 30% clay)
● Data collected by Gold (1978)
■ Data collected by Alberta Research Council
Lac La Biche
Sand River
Beaver River
Cold Lake
Muriel Lake
47-7
15-7
24-44
34-9
30-12
44-7
30-4
47-7
39-9
20-9
41-11
44-7
0
10
km
N

Figure 21. Regional differences in the grain size of the till in the Bronson Lake Formation.

Muriel Lake Formation

Source of name: Muriel Lake, Alberta, located in the south-central part of the Sand River map area, NTS 73L.

Type section: Alberta Environment test hole E802, located in LSD 5, Sec 32, Tp 61, R 5, W 4 Mer in the Sand River map area, NTS 73L (figure 17).

Type area: The area north of Muriel Lake around the village of Fort Kent in the Sand River map area, NTS 73L.

Reference sections: Alberta Environment test holes E804 (LSD 4, Sec 1, Tp 64, R 4, W 4 Mer), E1710 (LSD 16, Sec 9, Tp 62, R 5, W 4 Mer), E1712 (LSD 1, Sec 11, Tp 62, R 5, W 4 Mer), and E1708 (LSD 4, Sec 14, Tp 62, R 5, W 4 Mer).

Description of unit

The Muriel Lake Formation does not outcrop within the map area but is described from auger samples and drillers' records and is recognized in the subsurface from geophysical logs. The formation consists generally of silt, sand, and sand and gravel with minor silt and clay beds (table 2). In a few areas, such as in the segment of the Helina Valley west of Cold Lake (figure 9, cross section E1-E1', test hole E767) the formation is composed of clay interbedded with sand and gravel. Locally, the entire formation can be composed of silt and clay (test hole E833 in Tp 65, R 11).

Drillers' records describe small to medium-sized granitic and carbonate stones in the gravel, indicating a glaciofluvial or glaciolacustrine origin. Cobbles or boulders are uncommon. The sand is generally medium-grained and well-sorted, although in some test holes coarse sand was mapped. The deposits of the Muriel Lake Formation are described as unoxidized and have a light to medium gray color.

Distribution, thickness, and subcrop topography

The distribution and extent of the Muriel Lake Formation are shown in figure 22. The formation lies both within segments of the buried valleys and channels, overlying either the Bronson Lake Formation or the Empress Formation, and on the bedrock between the valleys. It has not been recognized in the highlands that lie north and south of the central part of the map area.

The top of the Muriel Lake Formation ranges in elevation from as high as 580 m between the Beverly and St. Paul valleys in the southwest, to as low as 490 m in the Beverly Valley in Tp 62, R 5 (figure 22). Although the surfaces of most of the stratigraphic units within the buried valleys dip to the northeast because of the regional slope, the Muriel Lake Formation lies atypically higher in the northeast and its surface there slopes southwest. The elevation of the formation rises from 530 m at the Beverly-Helina confluence (test hole E803, Tp 64, R 5), to about 545 m directly west of Cold Lake in Tp 65, R 2 (figure 9, cross section E1-E1', test hole E767).

The distribution of the Muriel Lake Formation can be defined by two trends that intersect near Moose Lake in Tp 61, R 7 (figure 22). The first trend originates within the Beverly Valley in the southwest corner of the map area and extends northeast, following the Helina Valley towards Cold Lake. The gap in the distribution of the formation in Tp 63-64, R 5-6, shown in figure 22, reflects the absence of information in that area.

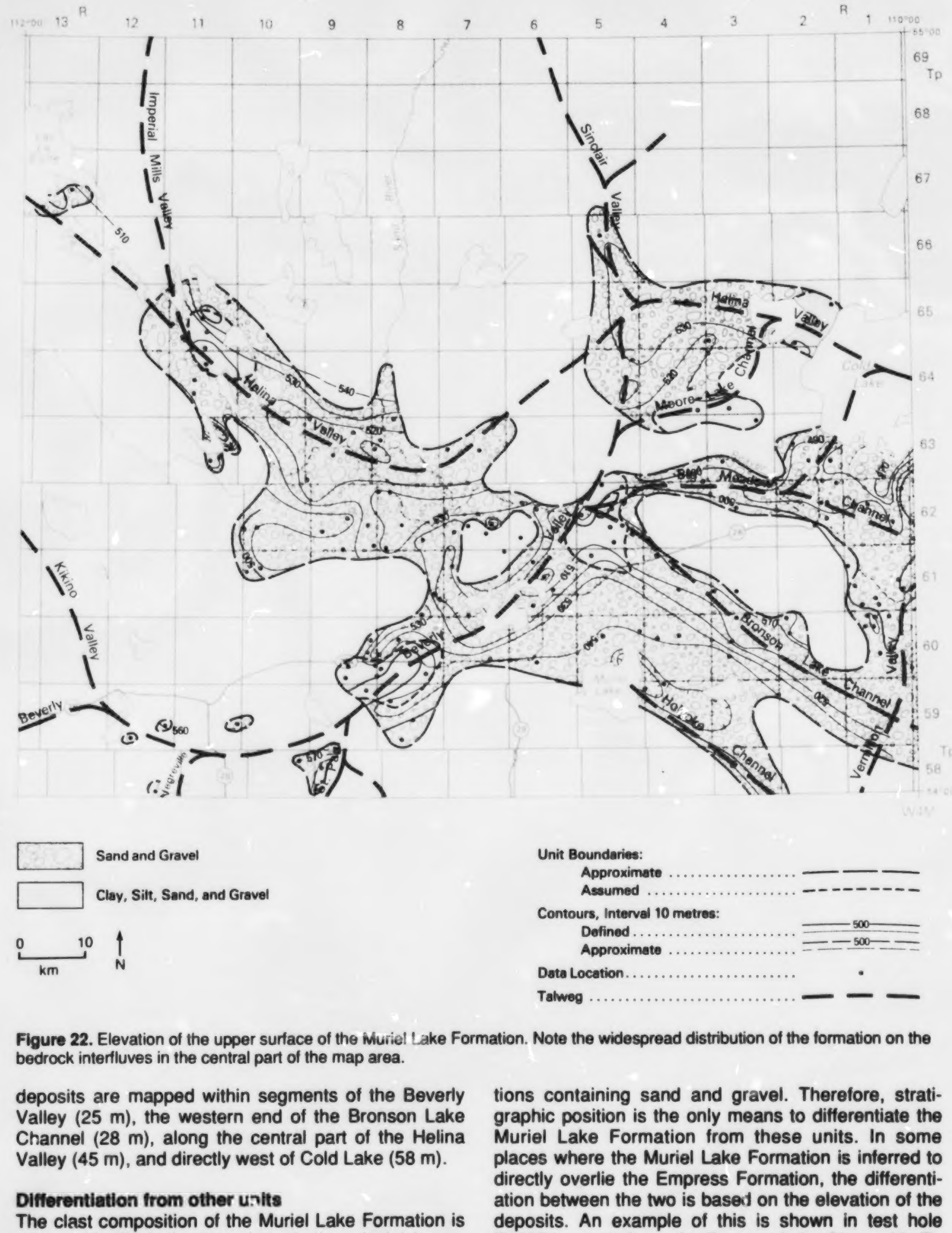
The second trend originates along the northwest end of the Helina Valley and extends southeast, following the orientation of the Bronson Lake and Big Meadow channels. Data are lacking for the northwest segment of this trend, and it is uncertain if the formation is absent between Tp 65, R 11 and Tp 67, R 13, as shown in figure 22. As previously discussed, it is uncertain if the sediments that are mapped as unit 3 of the Empress Formation in Tp 65-67, R 11-13, are in fact part of the Muriel Lake Formation. This is based on the nearly equivalent elevations of the top of unit 3 deposits in the Imperial Mills Valley and the top of Muriel Lake Formation deposits in the Helina Valley.

The Muriel Lake Formation extends out of the Helina Valley in Tp 63, R 7-10, forming a thin drape overtop the flat-lying bedrock as far south as Tp 61, R 10 (figure 22). A narrow band of the Muriel Lake Formation lies within an erosional depression that truncates the interfluve of the Helina and Beverly valleys south of Tp 63, R 8. This depression extends beneath the Sand River to the north (figure 9, cross section E3-E3', test hole E832) and connects to the Kehiwin Channel to the south (figure 4).

Although information is absent for the eastern part of the Bronson Lake Channel, the Muriel Lake Formation is projected eastward to connect with deposits that lie within the Vermilion Valley (figure 22). South of the Bronson Lake Channel the formation lies on the flat-lying bedrock surface, extending in an east-west direction for about 12 km (figure 23). The configuration of the formation in this area indicates that it forms a high level terrace along the south edge of the channel.

It is believed that the Muriel Lake Formation lies within most of the Big Meadow Channel, resting either on the bedrock surface or on top of unit 3 of the Empress Formation. The Bronson Lake Formation appears to have been eroded from most of the channel. Southeast of the channel, the formation forms a widespread cover on the bedrock between the Big Meadow Channel and the Vermilion Valley (figure 22).

The formation is generally thick throughout the map area, ranging between 10 and 20 m (figure 23). Thick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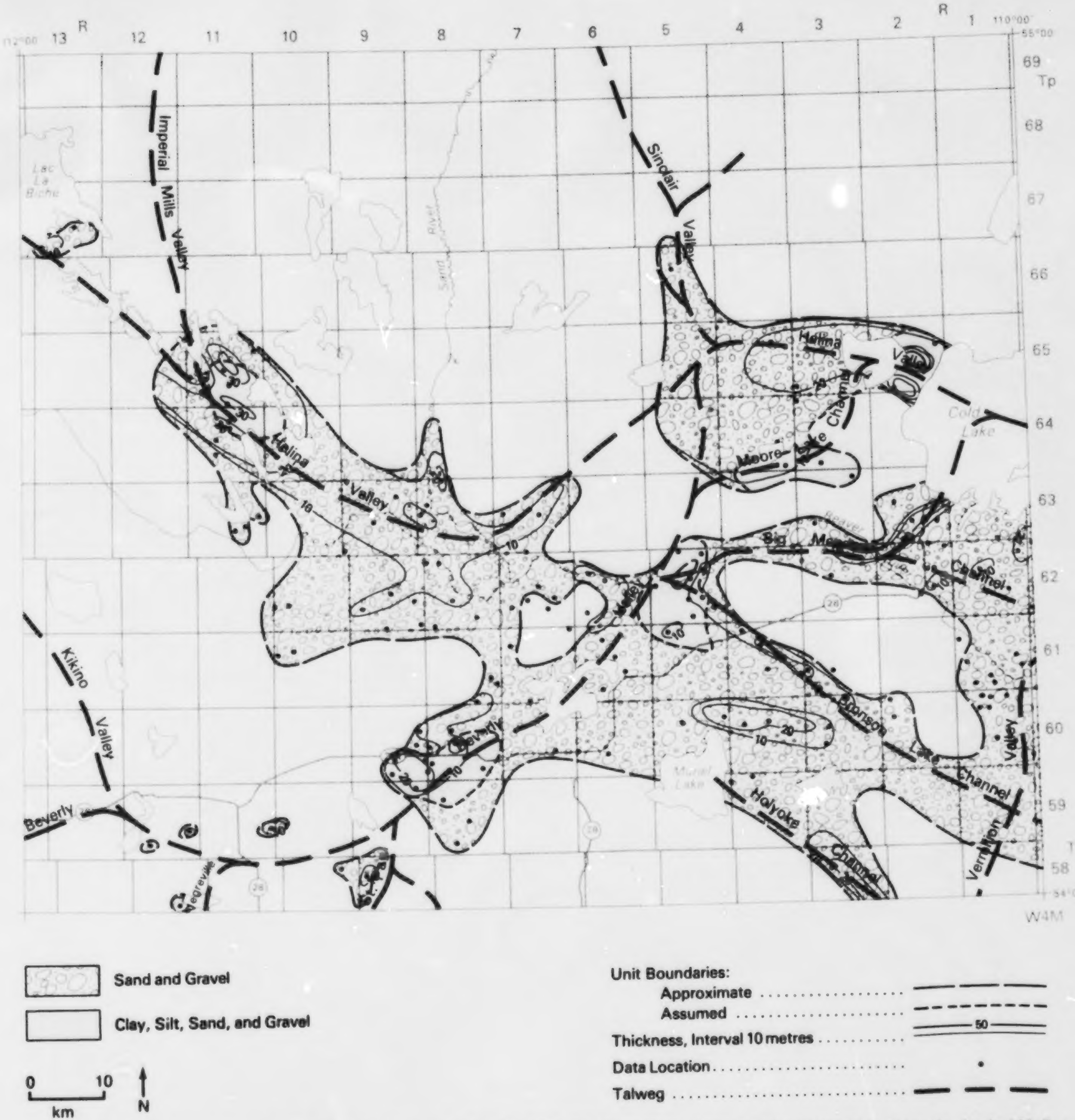
Tp
Imperial Mills Valley
Sinclair Valley
Helina Valley
Moore Lake Channel
Bronson Lake Channel
Kikino Valley
Beverly Valley
Beverly
Holyoke Channel
Vermilion Valley
Valley
510
540
530
520
560
570
630
620
610
490
600
Sand and Gravel
Clay, Silt, Sand, and Gravel
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Contours, Interval 10 metres:
Defined
Approximate
500
Data Location
Talweg

Figure 22. Elevation of the upper surface of the Muriel Lake Formation. Note the widespread distribution of the formation on the bedrock interfluves in the central part of the map area.

deposits are mapped within segments of the Beverly Valley (25 m), the western end of the Bronson Lake Channel (28 m), along the central part of the Helina Valley (45 m), and directly west of Cold Lake (58 m).

Differentiation from other units

The clast composition of the Muriel Lake Formation is not notably dissimilar from that of other glacial formations containing sand and gravel. Therefore, stratigraphic position is the only means to differentiate the Muriel Lake Formation from these units. In some places where the Muriel Lake Formation is inferred to directly overlie the Empress Formation, the differentiation between the two is based on the elevation of the deposits. An example of this is shown in test hole E1937 located above the Bronson Lake Channel in Tp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61
60
59
Tp
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54°00
W4M
Lac La Biche
Imperial Mills Valley
Sinclair Valley
Sand River
Helina Valley
Helina Valley
Helina Channel
Moore Lake Channel
Cold Lake
Beaver
Big Meadow Channel
Kikino Valley
Beverly
Beverly
Bronson Lake Channel
Vermilion Valley
Muriel Lake
Holyoke Channel
Negreville
10
20
28
Sand and Gravel
Clay, Silt, Sand, and Gravel
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location
Talweg

Figure 23. Thickness of clay, silt, sand, and gravel in the Muriel Lake Formation. Note the thick deposits along the buried Helina Valley and Bronson Lake and Big Meadow channels.

60, R 3. On the basis of stratigraphic position, a basal sand and gravel unit at this location should be strictly defined as unit 3 of the Empress Formation. However, the unit is thicker and lies at a higher elevation than unit 3 deposits in the western part of the channel. Furthermore, the Bronson Lake Formation that typically overlies unit 3 in the west is not recognized in this test hole. The Bronson Lake Formation was probably once present but was later eroded and the Muriel Lake Formation was subsequently deposited overtop the Empress Formation. This accounts for the greater thickness of fluvial sediment at this location.

Because of poor information, the differentiation between the Muriel Lake Formation and unit 3 of the Empress Formation is particularly difficult in the southwest, Tp 58-59, R 9-12.

Nature of contacts

The contact between coarse sediment of the Muriel Lake Formation and clayey diamicton of the Bronson Lake Formation is generally sharp (figure 9, cross section E2-E2', test holes E1708 and E1712). This contact is less easily defined where the base of the Muriel Lake Formation is composed of clay and silt (figure 12).

Generally the upper part of the Muriel Lake Formation is composed of sand, or sand and gravel, and the contact with diamicton of the overlying Bonnyville Formation is sharp.

Origin of the sediment in the Muriel Lake Formation

Not all of the sediment within the Muriel Lake Formation is considered to have the same origin, nor was it all deposited during the same event. The thick, widespread clay that lies at or near the base of the formation in a number of places within the Helina Valley (figure 5, test holes E833, E831, E1720, and E765) is probably glaciolacustrine sediment possibly deposited by proglacial lakes formed during the later phases of the Cherry Grove Glaciation. A glaciofluvial environment is interpreted in those areas where thin clay is interbedded with sand and gravel (figure 5, test holes E829, E802, and E804).

It is probable that most, though not all, of the sand and gravel of the Muriel Lake Formation is glaciofluvial sediment deposited during the later phases of the Cherry Grove Glaciation. Evidence for a glaciofluvial origin is the great thickness and channel-like distribution of the unit within the buried valleys and channels. The evidence for deposition during the later phase of the Cherry Grove Glaciation, rather than during the early phase of the Fort Kent Glaciation, is presented as follows: within segments of the buried valleys and channels, and on the upland south of the Bronson Lake Channel, the underlying Bronson Lake Formation is widespread and well preserved. It is believed that in this area the formation was protected from erosion during the following nonglacial period by the thick sequence of overlying sand and gravel of the Muriel Lake Formation. It is interpreted therefore, that the deposition of the gravel preceded the nonglacial period that followed and thus was associated with the later phases of the Cherry Grove Glaciation.

Stratigraphic evidence suggests that in the northeast segment of the Helina Valley, between Tp 65, R 2 and Tp 64, R 5, the Muriel Lake Formation was deposited in contact with an ice margin. Here, the top of the formation lies at a significantly higher elevation within this segment of the valley than it does in the western segment, even though the regional slope is to the northeast. This anomalously higher elevation of the top of the formation indicates that the unit was deposited by meltwater issuing from a glacier front in the form of an ice-contact outwash fan. This thick sequence of sand and gravel forms the core of the Medley Upland in the northeast part of the map area (figure 9, cross sections E1-E1' and E2-E2').

Bonnyville Formation

Source of name: Town of Bonnyville, Alberta, located in Tp 61, R 5, W 4 Mer in the Sand River map area, NTS 73L.

Type section: Alberta Geological Survey auger test hole T43, located in LSD 16, Sec 26, Tp 61, R 7, W 4 Mer in the Sand River map area, NTS 73L (figure 24).

Type area: The area around the town of Bonnyville, in the east-central part of the Sand River map area, NTS 73L.

Reference sections: Alberta Geological Survey auger test holes T16 (LSD 4, Sec 30, Tp 61, R 1, W 4 Mer), and T32 (LSD 9, Sec 2, Tp 64, R 3, W 4 Mer); Alberta Environment rotary test holes E802 (LSD 4, Sec 32, Tp 61, R 5, W 4 Mer), E1710 (LSD 16, Sec 9, Tp 62, R 5, W 4 Mer), and E1708 (LSD 4, Sec 14, Tp 62, R 5, W 4 Mer).

Description of formation

The Bonnyville Formation extends throughout the map area. It has not been observed in outcrop, but has been mapped from auger samples, rotary-drill cuttings, sidewall samples, and electric logs. The formation consists mainly of diamicton, characterized by an abundance of quartz in the very-coarse-sand fraction and by a paucity of calcareous material, particularly dolostone in the very-coarse-sand fraction and dolomite in the silt-clay fraction (table 2). On the basis of differences in grain size and electric logs, the Bonnyville Formation is divided into two units: unit 1, containing a clayey, low-resistance diamicton, overlain by unit 2, containing a sandy, high-resistance diamicton. In places stratified sediment consisting of clay, sand and gravel lies between diamicton of units 1 and 2; this sediment is included in unit 1 (figure 25). The two units of the Bonnyville Formation are described separately below.

Unit 1

Description of unit

Unit 1 of the Bonnyville Formation is recognized mainly from the electric logs, though some samples of the diamicton have been analyzed by Gold (1978) and in this study (Andriashek and Fenton 1979, test holes T23, T38, and T73). The diamicton is dark gray and the average grain size of the smaller-than-2-mm fraction is about 28% sand, 30% silt, and 42% clay (figure 18). The very coarse sand consists of about 61% igneous and metamorphic rock fragments, 33% quartz fragments, 3% limestone, 2% dolostone, and about 1% local rock types. The ranges in both grain size and very-coarse-sand composition are shown in table 3, appendix B. Calcareous material makes up 3% of the silt-clay fraction (Gold 1978; test hole E798).

Distribution, thickness, and topography

Unit 1 of the Bonnyville Formation lies only within segments of the Beverly, Helina, Vegreville, and Sinclair valleys and in the Holyoke Channel (figure 26). The unit is widespread in the southwest corner of the map area, overlying a segment of the Beverly and Vegreville valleys in Tp 58-60, R 8-14. Within much of this area unit 1 is overlain by unit 2 except for the extreme western part where unit 2 was probably eroded and where unit 1 forms the top of the formation. The top of unit 1 ranges in elevation from as much as 606 m in the southwest, Tp 58, R 10, to as low as 515 m near Truman, Tp 63, R 8 (figure 26).

Unit 1 has a discontinuous distribution within the Helina Valley. An example of this is in Tp 65, R 11, where unit 1 is recognized within only three of ten adjacent test holes. The most widespread deposit in the Helina Valley is mapped in Tp 64-65, R 3-8 (figure 26). Here, glaciofluvial sediment covers much of the diamicton. Unit 1 also extends northward from the Helina Valley into the Sinclair Valley in Tp 66-67, R 5 and onto the uplands flanking the north slope of the Helina Valley in Tp 64-65, R 6-7.

The thickest deposits of unit 1 are found in the western segment of the Beverly Valley near Spedden in Tp 59, R 13, where as much as 68 m have been mapped (figure 27). Thick deposits are also mapped in the Sinclair Valley (Tp 66, R 5) where 16 m of silt, clay, sand, and gravel overlie 27 m of diamicton (figure 9, cross section E2-E2', test hole E2075).

Differentiation from other units

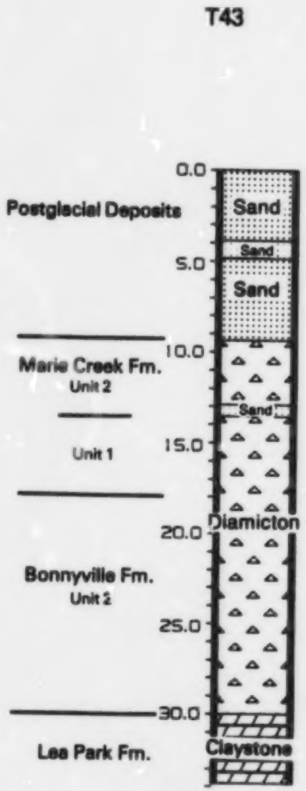
Diamicton of unit 1 is differentiated from the underlying Bronson Lake Formation mainly on the basis of stratigraphic position. The two units can only be differentiated where glaciofluvial sediment of the Muriel Lake Formation lies between them. Otherwise, as in the southwest corner of the map area, the differentiation is difficult because both have similar grain sizes and electric-log responses (figure 23, test hole E2075).

Differences in the electric-log responses are the most useful criteria for differentiating unit 1 from the overlying unit 2 of the Bonnyville Formation. Diamicton of unit 1 has much lower resistivity than unit 2, presumably because it is more clayey (figure 25).

Nature of contacts

Lower contact

Unit 1 overlies claystone and siltstone of the Belly River and Lea Park formations in many places. This contact is commonly gradational and difficult to recognize because unit 1 contains diamicton and glacially eroded bedrock material. The contact is particularly difficult to establish in Tp 59, R 13, around Spedden


T43
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30.0
Postglacial Deposits
Marie Creek Fm.
Unit 2
Unit 1
Bonnyville Fm.
Unit 2
Lea Park Fm.
Sand
Sand
Sand
Sand
Diamicton
Claystone

Alberta Geological Survey test hole: T43
Location: LSD 16 Sec 26 Tp 61 R 7 W 4 M NTS:73L

Elevation: 1800 ft, 549 m (estimated)
Date drilled: August 26, 1976 Logged by: M. Fenton

Depth (m)	Grain Size Properties					Silt and Clay Carbonate Content			1-2 mm Sand Petrology							
	Sand % >62.5μm	Silt %	Clay % <4μm	1-2 mm Sand %	Moisture %	CO_2 (cm³)	CO_3 %	Calcite / Dolomite	Igneous Metamorphic %	Quartz %	Quartzite Quartz Sandstone %	Limestone %	Dolostone %	Local %	Other	Total number of grains
10	40	24	36	1.9	14				68	26	1	3	3	0	0	240
11	36	31	33	2.5	12				56	20	0	6	16	2	0	314
12	40	35	25	2.5	10				61	19	0	4	14	3	0	309
13																
14	37	25	38	2.9	10				62	27	0	3	8	1	0	368
15	35	27	39	2.3	10				65	18	0	6	10	2	0	326
16	34	25	41	2.4	10				62	25	1	4	8	1	0	326
17	29	29	42	1.8	12				59	25	1	6	9	1	0	236
18	53	28	19	3.5	8				57	33	2	4	2	2	0	450
19	53	28	19	3.0	8				58	33	1	6	2	0	0	385
20	54	28	18	3.7					60	30	2	5	2	2	0	458
21	54	27	19	3.5	9				58	34	1	3	1	2	0	464
22	54	27	19	3.6	9				54	35	1	6	2	1	0	430
23	51	27	22	2.8	10				58	32	0	4	2	3	0	376
24	52	26	22	3.4	9				55	33	1	4	4	3	0	426
25	52	28	20	3.3	9				59	32	1	4	3	2	0	407
26	53	26	21	3.2	9				55	35	1	4	2	9	0	407
27	45	23	32	2.6	12				59	30	1	4	4	2	0	295
28	33	19	48	1.7	14				63	27	0	2	5	4	0	224
29	56	30	14	3.0	9				65	27	1	3	2	2	0	377

Figure 24. Type section of the Bonnyville Formation. Alberta Geological Survey test hole T43.

where diamicton of unit 1 is very clayey and nearly free of granules or pebbles (figure 10, cross section N2-N2', Chorney water-well log in LSD 9, Sec 28, Tp 59, R 12, W 4 Mer). Unit 1 has a sharp and well-defined contact with the underlying deposits of the Muriel Lake and Empress formations (figure 25).

Upper contact

Unit 1 can have either a sharp contact (test hole E798, Tp 59, R 9) or a gradational contact (Andriashek and Fenton 1979, test hole T38) with the base of unit 2. Above segments of the buried Beverly and Helina valleys, the contact between the two is marked locally by fluvial sediment that separates the two units (figure 9, cross section E2-E2', test holes E831 and E2075).

In the southwest corner of the map area, unit 1 forms the top of the Bonnyville Formation. In this area the unit is overlain by both silt, sand, and gravel of the Sand River Formation and diamicton of the Grand Centre Formation. In both settings the contact is sharp and well defined on the electric logs (figure 10, cross section N1-N1', water-well log in LSD 9, Sec 28, Tp 59, R 12).

Unit 2

Description of unit

Unit 2 consists of unoxidized, very dark gray (5Y 3/1) diamicton in the eastern part of the map area, and commonly oxidized olive brown (2.5Y 4/3) diamicton in the west. The smaller-than-2-mm size fraction of unit 2 is very sandy in the east, averaging about 48% sand, 28% silt, and 24% clay (figure 18). The range in grain size is shown in table 4 (appendix B) and figure 28. The unit is rich in granules and very coarse sand (about 3%), and pebbles and cobbles are common. The sandiness of the unit is also indicated by a low moisture content, ranging between 9 and 11%. In the east, unit 2 is easy to penetrate with an auger and samples are generally loose and crumbly on the auger flights.

Unit 2 is less sandy and more clayey in the western part of the map area. The average grain size of the smaller-than-2-mm fraction is about 36% sand, 33% silt, and 31% clay (figure 18). The range in grain size is shown in table 4 (appendix B) and figure 28. The greater amount of clay in unit 2 in the west results in a slightly greater moisture content, ranging between 9 and 13%, and causes the unit to be stiffer and more difficult to penetrate with an auger.

The very-coarse-sand fraction of unit 2 is much the same throughout the map area. The average compositional values, shown in figure 18, are about 58% igneous and metamorphic rock fragments, 34% quartz fragments, 3% limestone, 2% dolostone, less than 1% quartzite, and between 1 and 2% locally-derived rock fragments. The range in composition is shown in table 4 (appendix B).

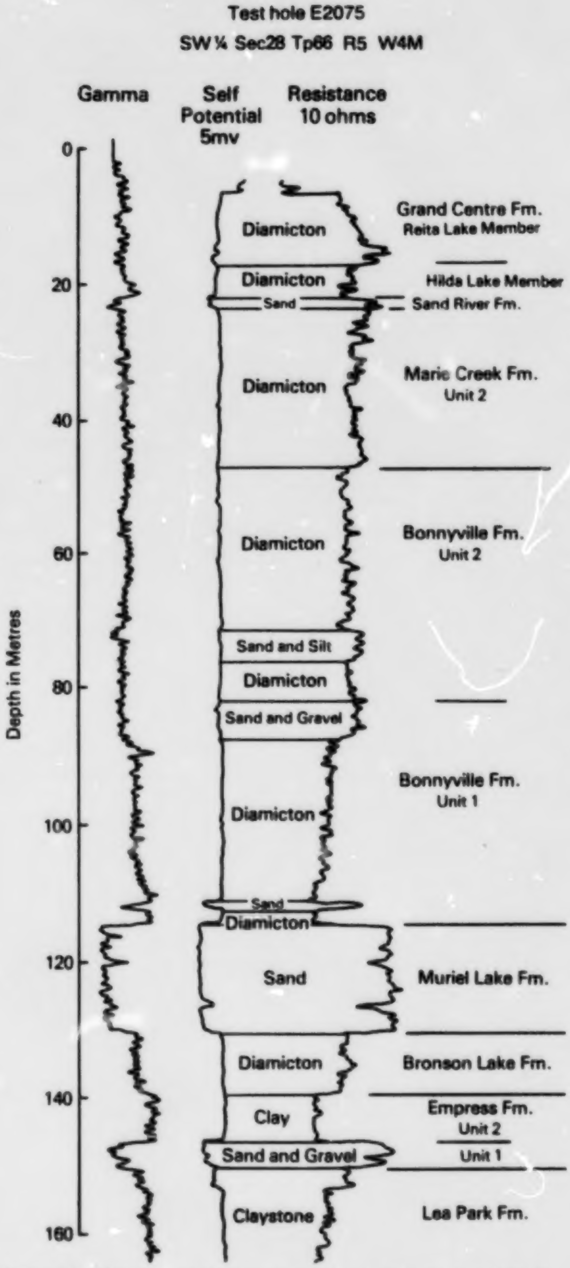
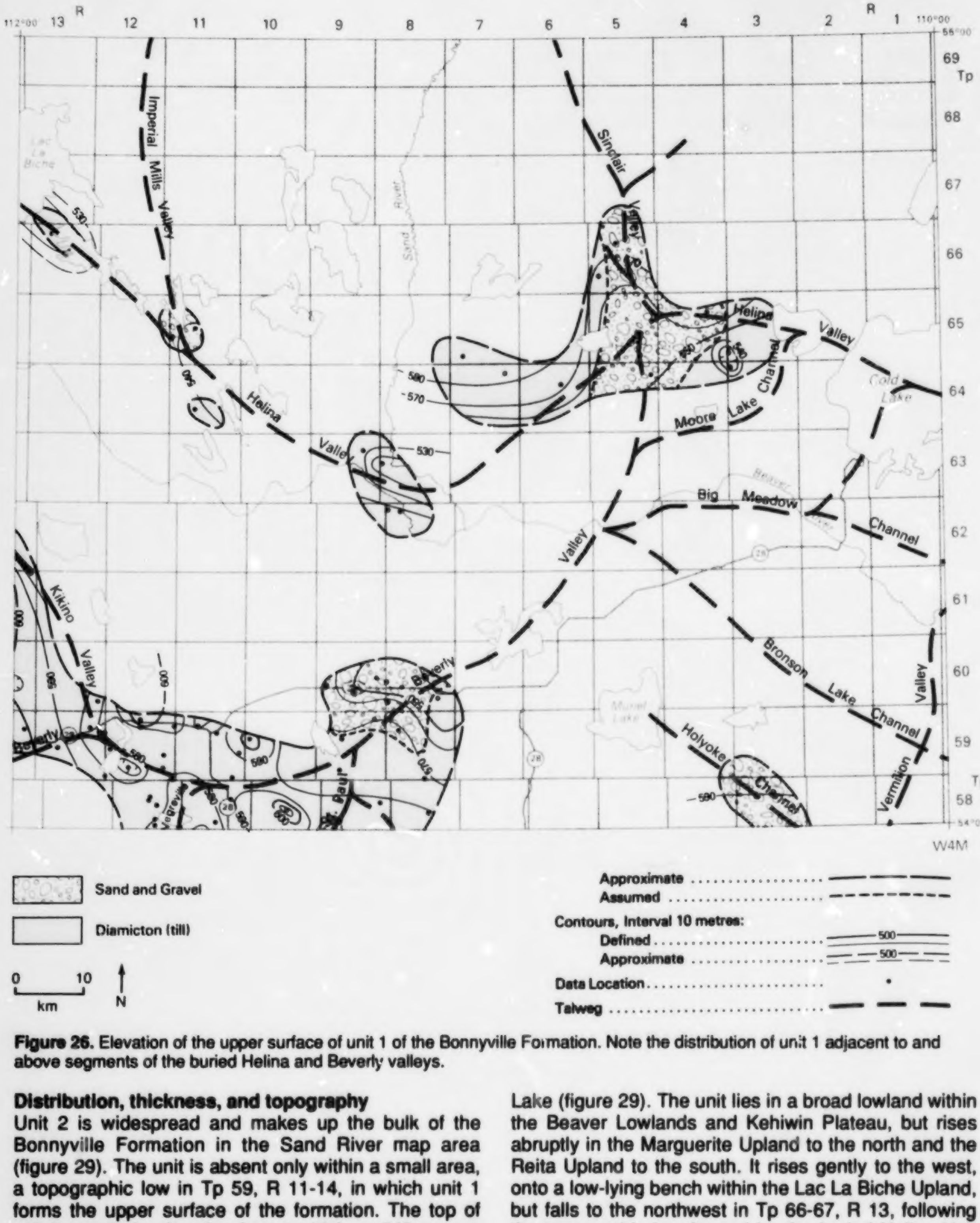


Figure 25. Electric and gamma-ray logs of units 1 and 2 of the Bonnyville Formation. Alberta Environment test hole E2075.

Calcareous material makes up 5 to 12% of the silt-clay fraction (calcite/dolomite ratio = 0.37, figure 18).

The clay mineralogy was determined for only a few samples of the sandy facies of unit 2. The clay consists of 40 to 50% illite, 25 to 40% kaolinite, 17 to 25% smectite, and 5 to 10% chlorite (appendix C).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Lac La Biche
Imperial Mills Valley
Sinclair Valley
Sand River
Helina Valley
Helina Valley
Moore Lake Channel
Cold Lake
Big Meadow Channel
Valley
Kikino Valley
Beverly
Beverly
Bronson Lake Channel
Holyoke Channel
Vermilion Valley
Muriel Lake
St. Paul
Vegreville
530
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600
590
500
Sand and Gravel
Diamicton (till)
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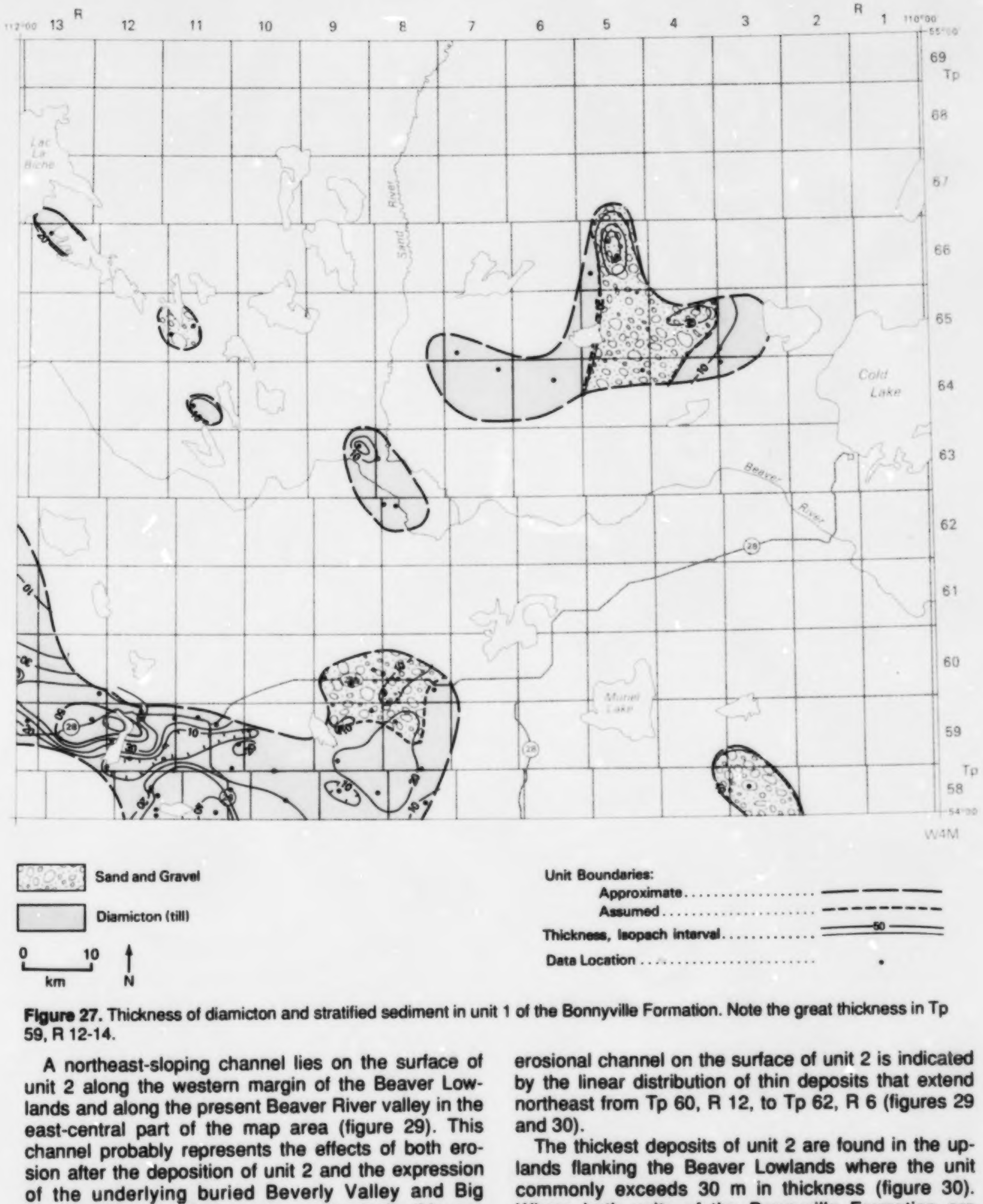
Approximate
Assumed
Contours, Interval 10 metres:
Defined
500
Approximate
500
Data Location
Talweg

Figure 26. Elevation of the upper surface of unit 1 of the Bonnyville Formation. Note the distribution of unit 1 adjacent to and above segments of the buried Helina and Beverly valleys.

Distribution, thickness, and topography

Unit 2 is widespread and makes up the bulk of the Bonnyville Formation in the Sand River map area (figure 29). The unit is absent only within a small area, a topographic low in Tp 59, R 11-14, in which unit 1 forms the upper surface of the formation. The top of unit 2 ranges in elevation from as high as 640 m on a high ridge in Tp 58, R 7, to as low as 490 m within a segment of the Big Meadow Channel south of Cold Lake (figure 29). The unit lies in a broad lowland within the Beaver Lowlands and Kehiwin Plateau, but rises abruptly in the Marguerite Upland to the north and the Reita Upland to the south. It rises gently to the west, onto a low-lying bench within the Lac La Biche Upland, but falls to the northwest in Tp 66-67, R 13, following the topographic low formed by the buried Helina Valley.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Sand and Gravel
Diamicton (till)
Unit Boundaries:
Approximate
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Thickness, isopach interval
50
Data Location
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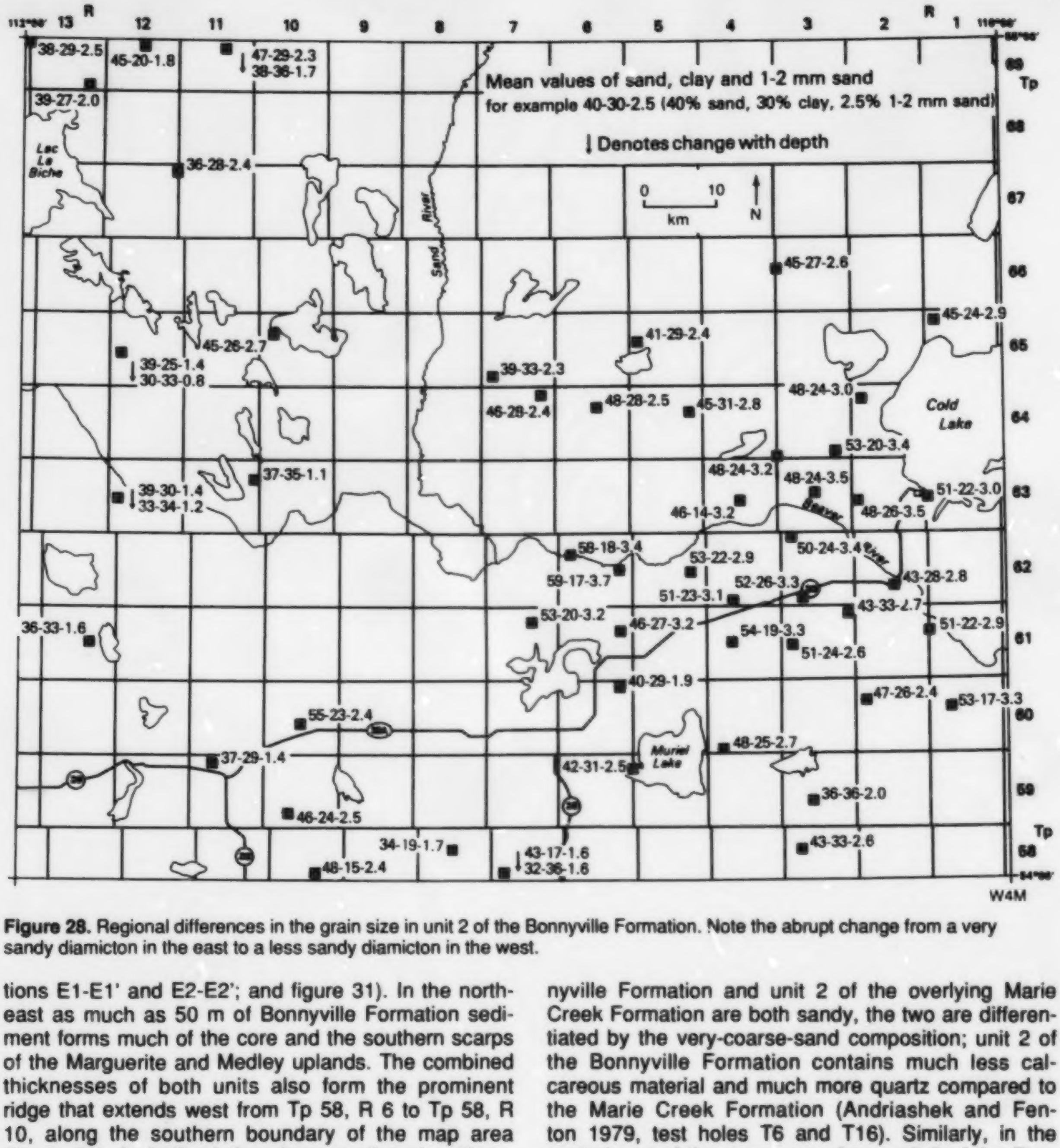
Figure 27. Thickness of diamicton and stratified sediment in unit 1 of the Bonnyville Formation. Note the great thickness in Tp 59, R 12-14.

A northeast-sloping channel lies on the surface of unit 2 along the western margin of the Beaver Lowlands and along the present Beaver River valley in the east-central part of the map area (figure 29). This channel probably represents the effects of both erosion after the deposition of unit 2 and the expression of the underlying buried Beverly Valley and Big Meadow Channel. Evidence for erosion is the thinness of the deposits in the channel, compared to thick deposits outside of the channel (figure 30). A similar erosional channel on the surface of unit 2 is indicated by the linear distribution of thin deposits that extend northeast from Tp 60, R 12, to Tp 62, R 6 (figures 29 and 30).

The thickest deposits of unit 2 are found in the uplands flanking the Beaver Lowlands where the unit commonly exceeds 30 m in thickness (figure 30). Where both units of the Bonnyville Formation are present, mainly within the uplands, their combined thicknesses locally exceed 40 m (figure 9, cross sec-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Mean values of sand, clay and 1-2 mm sand
for example 40-30-2.5 (40% sand, 30% clay, 2.5% 1-2 mm sand)
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Sand River
Cold Lake
Beaver River
Muriel Lake
38-29-2.5
45-20-1.8
47-29-2.3
38-36-1.7
39-27-2.0
36-28-2.4
45-27-2.6
45-24-2.9
45-26-2.7
39-25-1.4
30-33-0.8
41-29-2.4
39-33-2.3
46-28-2.4
48-28-2.5
45-31-2.8
48-24-3.0
53-20-3.4
37-35-1.1
39-30-1.4
33-34-1.2
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51-23-3.1
52-26-3.3
43-28-2.8
43-33-2.7
36-33-1.6
53-20-3.2
46-27-3.2
54-19-3.3
51-24-2.6
51-22-2.9
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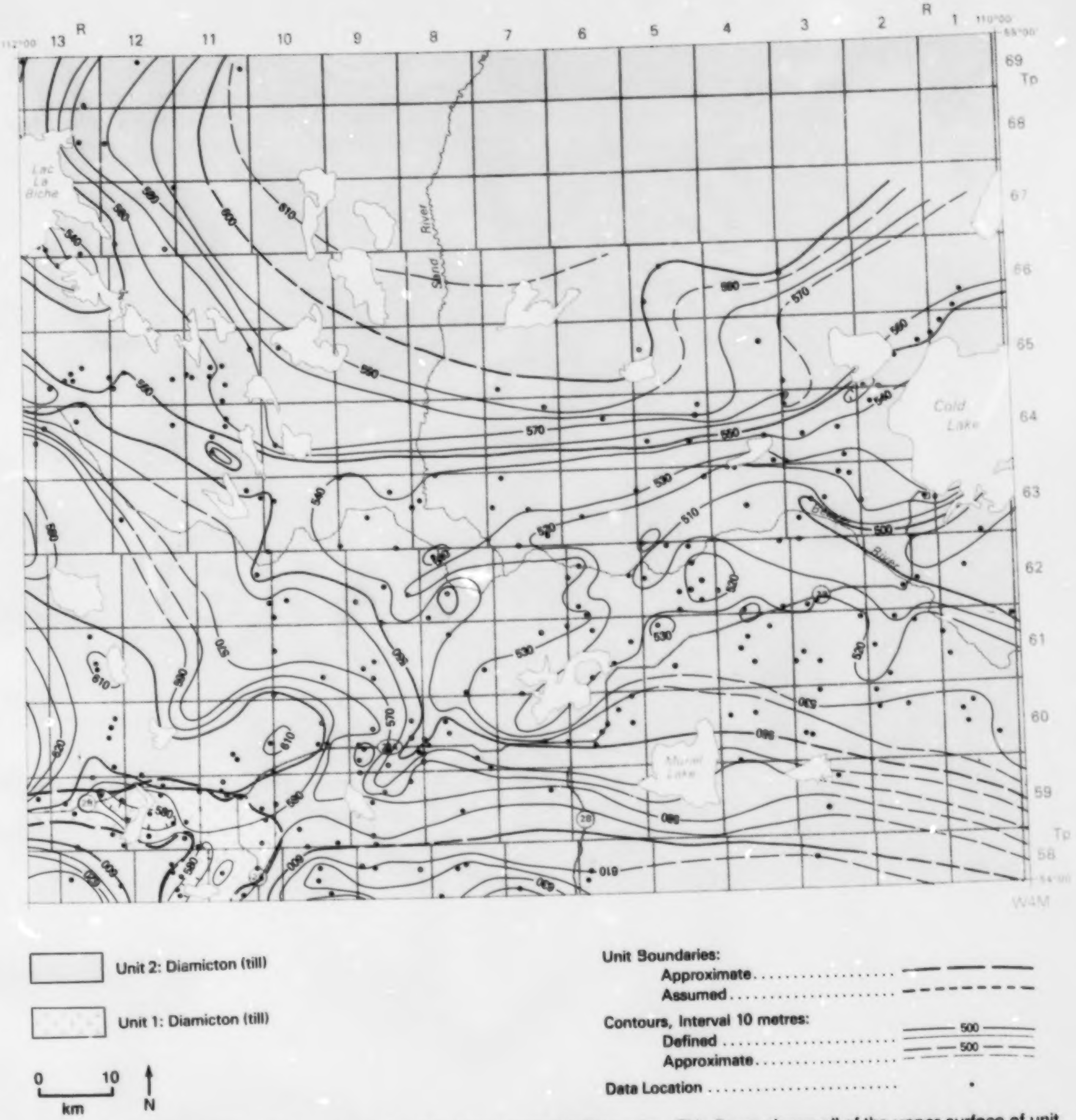
47-26-2.4
53-17-3.3
55-23-2.4
37-29-1.4
48-25-2.7
42-31-2.5
36-36-2.0
46-24-2.5
34-19-1.7
43-17-1.6
32-36-1.6
48-15-2.4
43-33-2.6

Figure 28. Regional differences in the grain size in unit 2 of the Bonnyville Formation. Note the abrupt change from a very sandy diamicton in the east to a less sandy diamicton in the west.

tions E1-E1' and E2-E2'; and figure 31). In the northeast as much as 50 m of Bonnyville Formation sediment forms much of the core and the southern scarps of the Marguerite and Medley uplands. The combined thicknesses of both units also form the prominent ridge that extends west from Tp 58, R 6 to Tp 58, R 10, along the southern boundary of the map area (figure 31). In both of the abovementioned settings, the thickness of the deposits indicates deposition along glacial ice margins.

Differentiation from other units

Unit 2 of the Bonnyville Formation is one of the coarsest-textured diamicton units in the map area, particularly in the amount of very coarse sand. Locally the unit can be differentiated by grain size alone. In the eastern part of the map area where unit 2 of the Bonnyville Formation and unit 2 of the overlying Marie Creek Formation are both sandy, the two are differentiated by the very-coarse-sand composition; unit 2 of the Bonnyville Formation contains much less calcareous material and much more quartz compared to the Marie Creek Formation (Andriashek and Fenton 1979, test holes T6 and T16). Similarly, in the central part of the map area where unit 2 of the Bonnyville Formation and the Kehiwin Lake Member of the Grand Centre Formation are both sandy, the two are differentiated by the abundance of very coarse sand and the abundance of quartz in the very-coarse-sand fraction of unit 2 (figure 18). In the west, where unit 2 and the overlying Vilna Member of the Grand Centre Formation are both clayey, the two are differentiated by the abundance of quartz, compared to igneous and metamorphic rock, in unit 2 (figure 18).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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
Unit 2: Diamicton (till)
Unit 1: Diamicton (till)
Unit Boundaries:
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Contours, Interval 10 metres:
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Data Location
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Figure 29. Elevation of the upper surface of unit 2 of the Bonnyville Formation. This figure shows all of the upper surface of unit 2, as well as part of the upper surface of unit 1 in the southwest where unit 2 is absent.

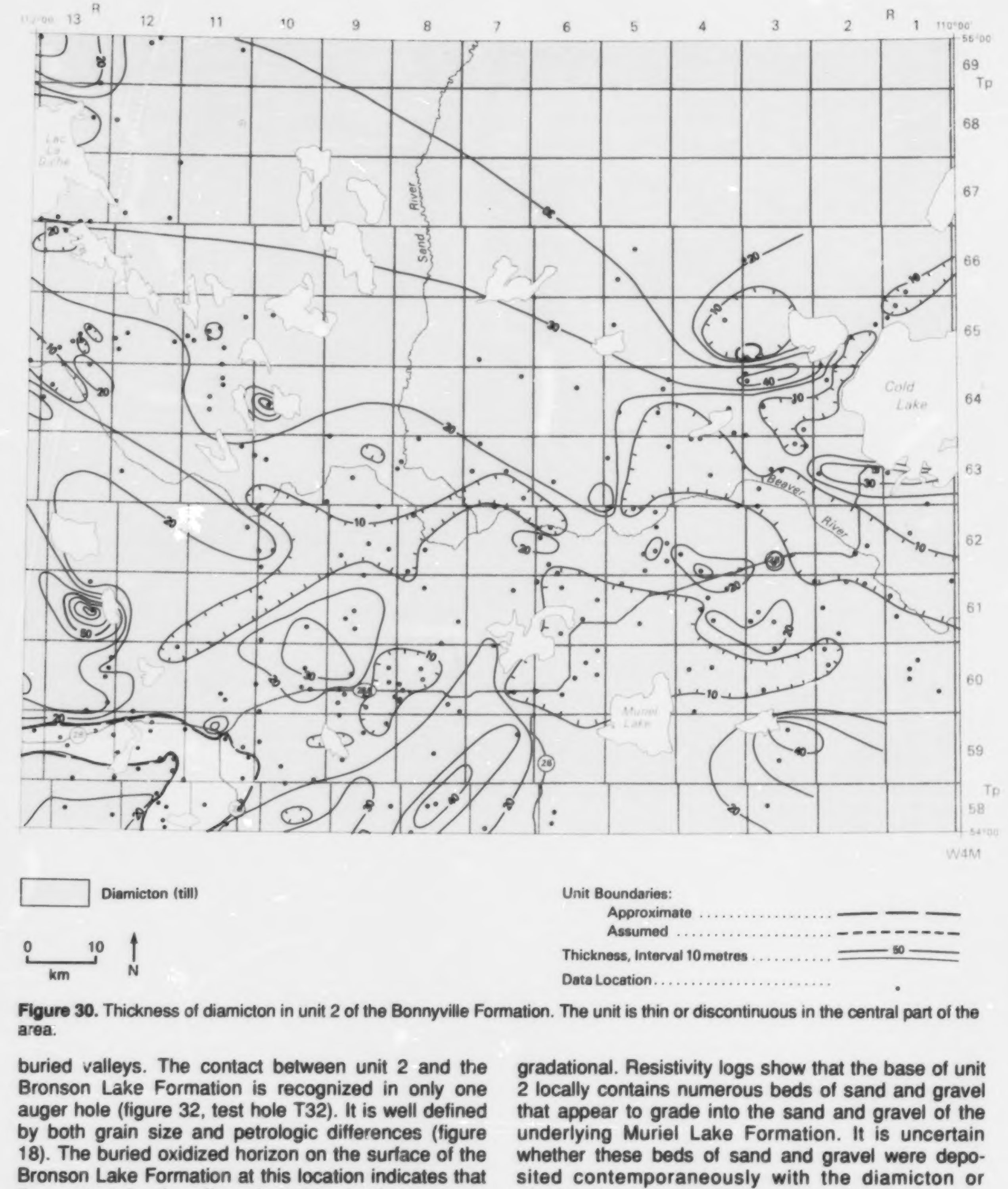
Electric logs are useful in differentiating diamicton of the Bonnyville Formation from diamicton of other units. The logs generally show a distinct break at the contact of the Bonnyville Formation with the other units. For example, over most of the east half of the map area units 1 and 2 of the Bonnyville Formation are generally more conductive than the upper part of the overlying Marie Creek Formation (figure 5, test holes E802, E804, E1708, E1712, and E1771).

Nature of contacts

Lower contact

Unit 2 overlies claystone of the Lea Park Formation in many places on the bedrock uplands. The contact is generally sharp, even though the amount of clay increases locally toward the base of unit 2 (Andriashek and Fenton 1979, test hole T9).

Unit 2 overlies diamicton or clay, silt, sand, and gravel of older Pleistocene units above the major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Sand River
Cold Lake
Beaver River
Muriel Lake
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Diamicton (till)
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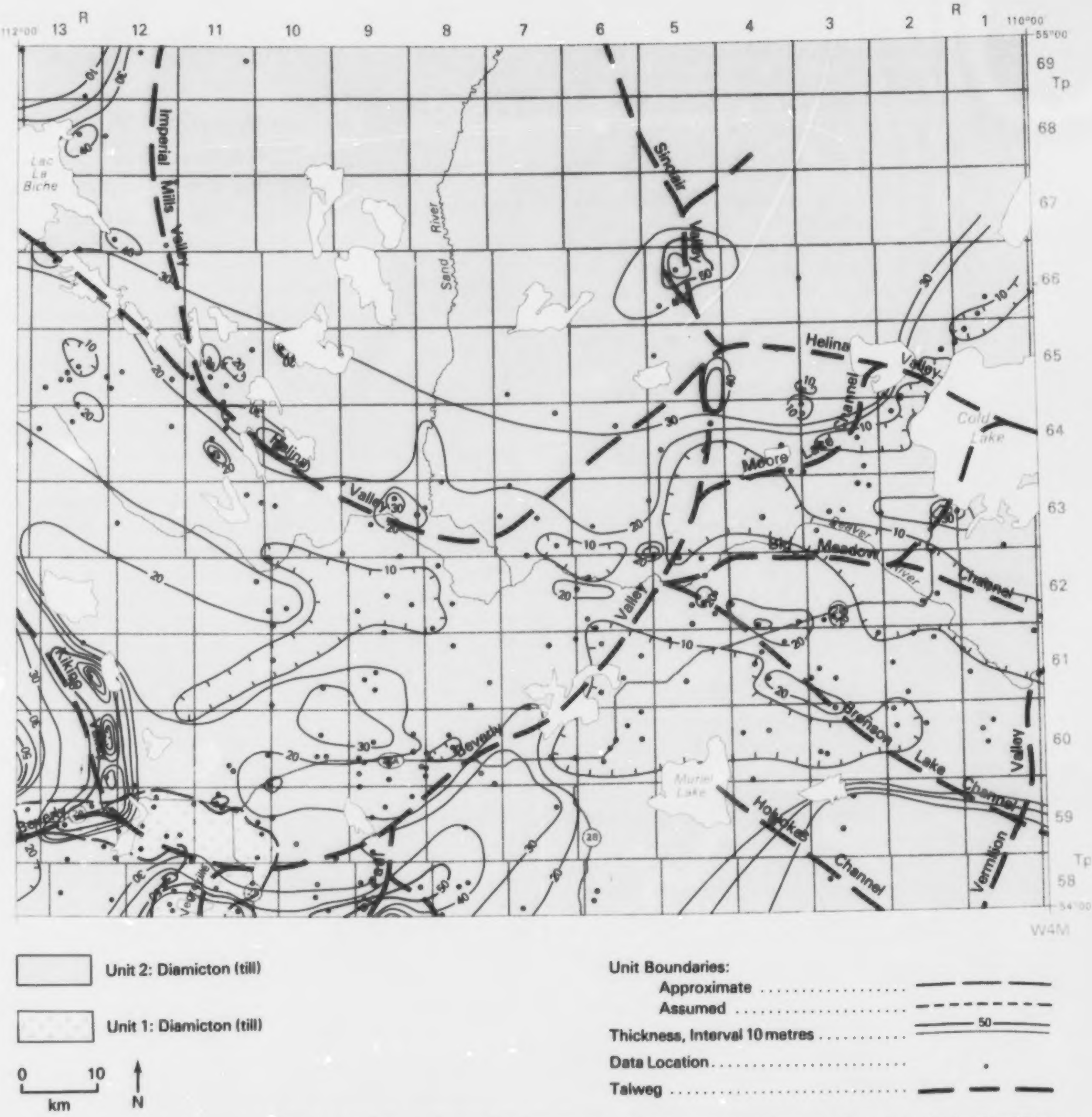
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
Data Location

Figure 30. Thickness of diamicton in unit 2 of the Bonnyville Formation. The unit is thin or discontinuous in the central part of the area.

buried valleys. The contact between unit 2 and the Bronson Lake Formation is recognized in only one auger hole (figure 32, test hole T32). It is well defined by both grain size and petrologic differences (figure 18). The buried oxidized horizon on the surface of the Bronson Lake Formation at this location indicates that the contact is also disconformable. In those places where unit 2 overlies clay, silt, sand, and gravel of the Muriel Lake Formation the contact can be sharp or gradational. Resistivity logs show that the base of unit 2 locally contains numerous beds of sand and gravel that appear to grade into the sand and gravel of the underlying Muriel Lake Formation. It is uncertain whether these beds of sand and gravel were deposited contemporaneously with the diamicton or whether they are glacially incorporated lenses of the underlying Muriel Lake Formation.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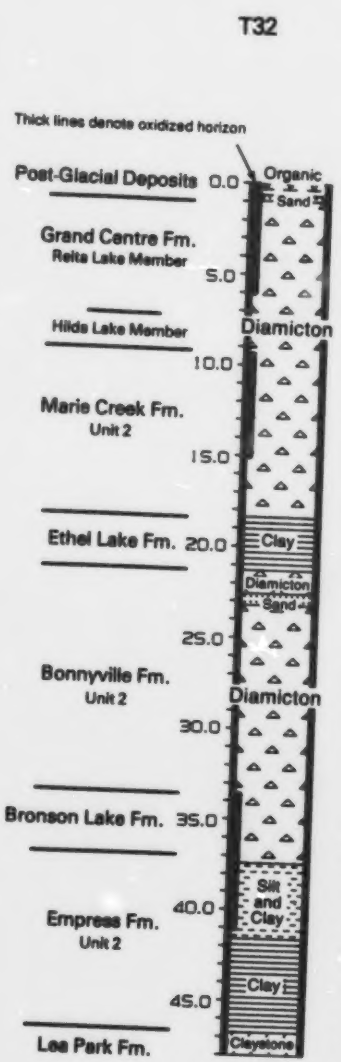
Imperial Mills Valley
Sinclair Valley
Sand River
Helina Valley
Moore Lake Channel
Cold Lake
Big Meadow Channel
Beaver River
Kikino Valley
Beverly Valley
Bronson Lake Channel
Muriel Lake
Holyoke Channel
Vermilion Valley
Unit 2: Diamicton (till)
Unit 1: Diamicton (till)
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
Data Location
Talweg

Figure 31. Total thickness of units 1 and 2 of the Bonnyville Formation. (Note the great thickness adjacent to the buried Kikino valley.)

Upper contact

Unit 2 has generally a sharp contact with clay, silt, sand, and gravel of the Ethel Lake and Sand River formations (figure 10, cross section N1-N1'). Where unit 2 is overlain by diamicton of the Marie Creek or Grand Centre formations, the contact is interpreted to be disconformable on the basis of the weathering on the surface of unit 2 (figure 10, cross sections E1-E1'and E3-E3'). In the western part of the map area this oxidized zone is widespread and can be easily recognized from drill samples.

The grain size and very-coarse-sand composition, particularly the amount of carbonates, of the overlying Marie Creek Formation is locally gradational with those same properties at the top of unit 2 of the Bonnyville Formation (Andriashek and Fenton 1979, test holes T25, T32, and 77SR3). This probably indicates that the top of the Bonnyville Formation was glacially


T32
Thick lines denote oxidized horizon
Post-Glacial Deposits
Organic
Sand
Grand Centre Fm.
Reita Lake Member
Hilda Lake Member
Diamicton
Marie Creek Fm.
Unit 2
Ethel Lake Fm.
Clay
Diamicton
Sand
Bonnyville Fm.
Unit 2
Diamicton
Bronson Lake Fm.
Silt and Clay
Empress Fm.
Unit 2
Clay
Claystone
Lea Park Fm.
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0

Alberta Geological Survey test hole: T32
Location: SW of LSD 12 Sec 1 Tp 64 R 3 W 4 M NTS:73L

Elevation: 1800 ft, 549 m
Date drilled: August 6, 1976 Logged by: L. Andriashek.

Depth (m)	Grain Size Properties					Silt and Clay Carbonate Content			1-2 mm Sand Petrology							
	Sand % >62.5μm	Silt %	Clay % <4μm	1-2 mm Sand %	Moisture %	CO_2 (cm³)	CO_3 %	Calcite/Dolomite	Igneous Metamorphic %	Quartz %	Quartzite Quartz Sandstone %	Limestone %	Dolostone %	Local %	Other	Total number of grains
1	37	26	37	1.9	13	21	9	0.2	70	24	1	2	4	0	0	266
2	36	25	38	1.8	15	29	12	0.4	66	29	1	2	3	0	0	249
3	36	25	39	2.0	16	26	11	0.2	66	28	1	3	2	0	0	270
4	37	26	37	1.7	15	26	11	0.3	64	27	3	1	4	1	0	239
5	34	26	41	3.0	15	26	12	0.3	64	27	1	4	4	0	0	230
6	32	26	42	1.9	14	26	11	0.2	64	27	2	3	4	0	0	233
7	33	28	39	1.7	12				69	19	3	3	5	1	0	225
8	26	28	46	1.1	14	25	11	0.2	69	22	0	4	5	0	0	173
9	20	31	49	0.7	14	28	12	0.3	59	30	0	3	9	1	0	114
10	38	30	31	2.4	8	44	18	0.2	67	16	0	3	11	2	0	161
11	40	30	31	2.5		41	17	0.2	66	16	1	3	13	1	0	320
12	40	26	31	2.4	10	44	18	0.2	66	20	0	2	10	2	0	296
13	41	28	32	2.4	8	39	16	0.2	63	20	2	5	9	2	0	312
14	46	27	27	2.5	9				61	24	1	4	7	2	0	324
15	51	27	21	3.5	7	29	12	0.3	59	30	1	3	5	1	0	477
16	55	23	22	3.1	7	30	13	0.3	57	32	0	5	5	2	0	413
17	56	23	22	2.8	7	31	13	0.2	56	35	1	3	3	2	0	404
18	46	27	28	2.6	8	29	12	0.3	59	31	0	2	5	3	0	333
19					20											
20					19											
21	31	25	44	1.2	16	16	7	0.4	49	45	3	1	1	1	0	151
22	40	25	35	2.7	12				54	40	2	3	0	1	0	388
23	52	30	18	3.2	9	21	9	0.4	59	35	2	3	1	1	0	438
24	53	26	19	3.4	9				53	41	1	2	2	2	0	474
25	52	29	19	3.4	9	21	9	0.3	58	36	1	1	1	3	0	450
26	53	29	18	3.4	9				61	34	1	2	1	2	0	427
27	53	28	19	3.3	8	21	9	0.3	60	35	0	3	2	0	0	436
28	54	26	20	3.4	8				59	34	2	2	2	1	0	443
29	53	26	21	3.4	8	20	8	0.3	56	38	0	2	1	3	0	484
30	53	26	22	3.6	9				61	34	1	2	2	1	0	483
31	54	25	21	4.6	10	19	8	0.3	56	36	1	3	2	3	0	596
32	53	25	22	3.8	8				54	38	1	3	2	1	0	497
33	23	34	43	0.7	12	20	9	0.4	38	45	3	4	2	8	0	115
34	24	34	43	0.8	13				58	28	0	5	3	6	0	120
35	23	34	43	0.8	14	21	9	0.3	58	28	0	5	3	6	0	120
36	24	31	45	0.8	12				34	44	0	4	6	12	0	108
37	6	41	53	0.1	17				21	18	0	0	4	57	0	28
38					19											
39					16											
40					18											
41					15											
42					16											
43					18											
44					16											
45					18											
46					20											
47					20											

Figure 32. Type section of the Ethel Lake Formation. Alberta Geological Survey test hole T32.

eroded and incorporated into the base of the overlying diamicton.

Origin and differences in the properties of the sediment in the Bonnyville Formation

The diamicton of units 1 and 2 of the Bonnyville Formation is interpreted to be till that was deposited during the second known glaciation in the map area, here named the Fort Kent Glaciation. Evidence to support a major glacial advance, rather than a readvance of the Cherry Grove Glaciation, is speculative, but consists of the following: the thick deposits of sand and gravel of the underlying Muriel Lake Formation indicate that an ice-free period followed the deposition of the Bronson Lake till. As well, in one location in the east, oxidation pervades throughout the upper part of the Bronson Lake till, which probably indicates that a prolonged nonglacial weathering period occurred before burial by the Bonnyville till.

The scarcity of carbonates and abundance of quartz in the very-coarse-sand fraction supports a source to the northeast. The scarcity of carbonates suggests either that the carbonates were ground finer than very coarse sand during glacial transport, or that only few exposures of carbonates were glacially eroded. If the first hypothesis were true, one might expect to see an increase in the amount of carbonate in the silt-clay fraction because of pulverization. However, in comparing the carbonate content of the silt-clay fraction of the Bonnyville till to the carbonate content in the Marie Creek till (figure 18), which also has a source to the north or northeast, it is evident that there is less carbonate in all grain sizes (smaller than 2 mm) in the Bonnyville till. Therefore, pulverization of carbonates during transport is probably not the reason for the smaller amount of carbonate in the Bonnyville till. Rather, the second hypothesis, that the Bonnyville till was deposited by a glacier that advanced over fewer exposed areas of carbonate rock, appears more probable. Such areas where carbonate rock do not subcrop beneath the overlying glacial drift are found directly northeast of the Sand River map area, in Saskatchewan, where Devonian carbonate rock is buried by Cretaceous rock (Geological Map of Saskatchewan, Whitaker and Pearson 1972).

The abundance of both quartz and sand in the till of unit 2 indicates that a considerable amount of quartz sand was eroded during glaciation. Two possible sources are considered: a more distant source, quartz sandstone of the Athabasca Formation, which outcrops along the southern edge of the Shield, and a local source, widespread sand and gravel of the underlying Muriel Lake Formation in the Beaver Lowlands and Kehiwin Plateau. The similarity in composition of the very coarse sand of both units 1 and 2 throughout the map area (tables 3 and 4, appendix B), in particular the quartz component, supports a more distant source, the Athabasca Formation.

The silty-clay till of unit 1 probably results from glacial erosion and incorporation of claystone and siltstone. Within the Kikino Valley and directly north of Spedden in Tp 59-60, R 13, a very thick sequence of coal, claystone, siltstone, and sandstone of the Belly River Formation, as well as preglacial gravel, was glacially displaced to form the base of the Bonnyville Formation (figure 10, cross section E4-E4', test hole R81SR1). South of Spedden, however, in Tp 59, R 13, water-well drillers' records describe the material to consist of clay with a few pebbles, in places resembling claystone. Here, glacial pulverization has probably ground the displaced rock sufficiently to produce a clayey till, unit 1. A similar sequence of glacially-displaced sediment from the Belly River Formation was mapped by Gold (1978) in parts of the Beverly Valley directly southwest of the Kikino Valley in the Tawatinaw map area, NTS 83I.

It is uncertain whether units 1 and 2 of the Bonnyville Formation were deposited during separate advances of the Fort Kent Glaciation or whether they reflect variations in grain size of a single till unit deposited during one glacial advance. Along the Helina Valley in the north and along the Beverly Valley in the southwest two advances are indicated on the basis of the widespread and thick sequence of fluvial sand and gravel that separates diamicton of units 1 and 2 (figures 9 and 10, cross sections E2-E2' and E4-E4'). Other evidence for two advances is from resistivity logs that in many places show a sharp, nongradational contact between diamicton of units 1 and 2. This sharp contact can be interpreted to be a depositional break, perhaps indicating two separate glacial advances. However, sharp textural contacts have also been noted within till that, on the basis of sand composition, was deposited during a single event unit (see description of Marie Creek Formation). It therefore seems more likely that unit 1 can be considered to be a grain-size facies of a single till sheet. A particularly good example of this is in Tp 59-60, R 12-13 where the contact between units 1 and 2 can be either sharp or gradational, reflecting differences in the amount of erosion of the underlying Lea Park and Belly River formations. In some places in this area blocks of displaced claystone have remained more or less intact at the base of the Bonnyville Formation, forming sharp contacts with the diamicton; in other places these blocks were fragmented and comminuted to produce a very clayey lower till that grades into a less clayey upper till.

Tables 3 and 4 (appendix B) show that the within-hole differences in grain size and sand composition of the till of units 1 and 2 are generally small, differing not more than 5%, and commonly less than 3%, from the mean. The between-hole differences on the other hand, especially for the grain-size properties, are greater though generally are smaller than the differences between other formations (figure 18). As an example, in the eastern two-thirds of the map area the grain size distribution of unit 2 differs by as much as 10% but nonetheless it contains the sandiest diamicton and can be correlated by grain size alone.

There are differences in the properties of the till within the Bonnyville Formation, particularly till of unit 2, that are striking. The most impressive is the abrupt change in the grain size of unit 2, from sandy till in the eastern two-thirds of the map area to clayey till in the west. This change occurs across a north-south trend that runs essentially along the west edge of R 10 (figure 28). The sandy eastern facies apparently overlies the clayey facies along this trend (Andriashek and Fenton 1979, test holes 77SR2, 77SR21, and 77SR28). This transition from a sandy to a clayey till possibly reflects a change in the underlying source. In the eastern and central parts of the map area the Bonnyville Formation overlies widespread sand and gravel of the Muriel Lake Formation, and glacial erosion of this coarse sediment may have contributed sand to the till. In the west, the Muriel Lake Formation is not nearly as widespread and the Bonnyville Formation directly overlies claystone and siltstone. Incorporation of this fine-grained sediment probably accounts for the greater amount of silt and clay in both units 1 and 2 in the west. The clayey facies of unit 2 in the west may also represent a gradational contact with the underlying clayey unit 1. The compositions of the very coarse sand of units 1 and 2 are similar, indicating that glacial erosion of the local rock enriched only the finer fraction of unit 2 in the west, without affecting the composition of the very coarse sand.

The presence of a poorly developed oxidized zone in the upper part of the Bonnyville Formation in a few places in the east (Andriashek and Fenton 1979, test hole T41) and a widespread, well-developed oxidized zone in the upper part of the formation in the west (Andriashek and Fenton 1979, test holes 77SR11, 77SR15, and 77SR21) are evidence that the Bonnyville Formation was exposed and weathered during a later period.

Ethel Lake Formation

Source of name: Ethel Lake, Alberta, located in Tp 64, R 3, W 4 Mer in the Sand River map area, NTS 73L.

Type section: Alberta Geological Survey auger test hole T32, located in LSD 12, Sec 1, Tp 64, R 3, W 4 Mer in the northeast part of the Sand River map area, NTS 73L (figure 32).

Type area: The area around Ethel Lake within the Beaver Lowlands in the east-central part of the Sand River map area, NTS 73L.

Reference sections: Alberta Geological Survey auger test holes T5 (LSD 2, Sec 16, Tp 59, R 3, W 4 Mer), T13B (LSD 1, Sec 30, Tp 60, R 2, W 4 Mer), and T15 (LSD 16, Sec 20, Tp 60, R 1, W 4 Mer); Alberta Environment test holes E1708 (LSD 4, Sec 14, Tp 62, R 5, W 4 Mer), E1937 (LSD 12, Sec 33, Tp 60, R 3, W 4 Mer), and E1948 (LSD 4, Sec 17, Tp 60, R 3, W 4 Mer).

Reference area: The area around Reita Lake within the Reita Upland in the southeast corner of the Sand River map area, NTS 73L.

Description of unit

The Ethel Lake Formation consists mainly of silt and clay with smaller amounts of sand and gravelly sand (table 2). The formation is mapped with certainty only in those places where it overlies the Bonnyville Formation and in turn is overlain by the Marie Creek Formation. The formation does not outcrop in the map area but is recognized from auger samples, rotary-drill cuttings, and geophysical logs, primarily electric logs.

Silt and clay of the formation are typically gray (5Y 4/1). Oxidized horizons are not recognized within or at the surface of the formation in any of the test holes. Distorted partings and laminations of silt and clay layers in the auger samples indicate bedding within the unit. The silt partings react mildly to the application of 10% HCl acid in field tests. The silt and clay have between 14 and 20% water and typically are soft and easy to penetrate with an auger.

Coarser sand and gravel make up a minor amount of the formation although their extent is widespread. The sand differs from fine to coarse-grained and is generally well sorted. The pebbles were not examined in detail but were described in the field as "typical glacial sand and gravel", with pebbles derived from the Canadian Shield as well as the local rock. In much of the southwest part of the map area the sand and gravel is interbedded with finer silt and clay.

Distribution, thickness, and subcrop topography

The Ethel Lake Formation is widespread, but not continuous, in most of the central and southeastern parts of the map area (figure 33). It was not recognized in the uplands to the north or southwest. The elevation of the formation decreases northeastward from 615 m in Tp 58, R 3 along the southern edge of the map area to 510 m in the Beaver Lowlands. In these lowlands the distribution of the formation is characterized by a number of large areas where the unit is absent (figure 33).

Silt and clay in the formation is both widespread and thick, forming a broad arc that extends from the Lac La Biche area in Tp 67, R 12, southeastward to the Reita Lake area in Tp 59, R 3 (figures 33 and 34). Along the western part of the map area, the formation is composed of silt and clay that is either overlain by sand and gravel or interbedded with sand and gravel (figure 33). This interbedded sequence is thick (10 to 20 m) in the area from Tp 59, R 7 in the Kehiwin Plateau northwestward to Tp 65, R 12 in the Lac La Biche Upland (figure 34).

In the central part of the map area above segments of the buried Helina and Beverly valleys the Ethel Lake Formation is characterized by a sand and gravel veneer (figure 34). Although this coarse sediment is considered to be widespread, the data are not sufficient to be certain that the distribution is as continuous as shown.

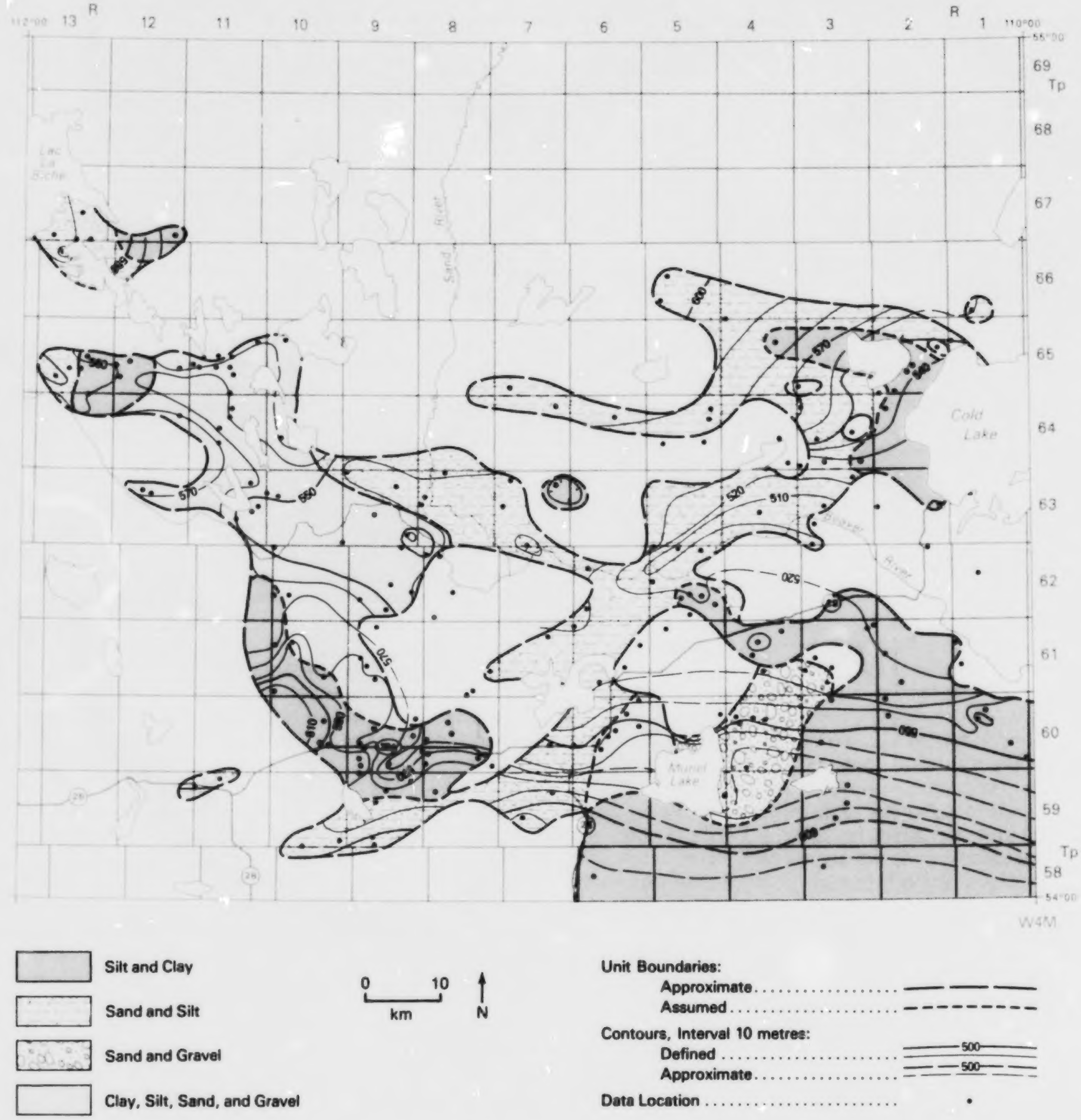
Differentiation from other units

The Ethel Lake Formation is differentiated from other units containing clay, silt, sand, and gravel primarily by stratigraphic position. It can be recognized with certainty only in those areas where it overlies diamicton of the Bonnyville Formation and where it, in turn, is overlain by diamicton of the Marie Creek Formation. In the southwest corner of the map area, where the overlying Marie Creek Formation is absent, the Ethel Lake Formation is difficult to differentiate from sand and gravel of the Sand River Formation (figure 10, cross sections E4-E4' and N1-N1'). This problem is resolved by assuming that all clay, silt, sand, and gravel deposits that overlie the Bonnyville Formation, and that are overlain by the Grand Centre Formation, are the stratigraphically higher Sand River Formation. It is therefore possible that in the southwest corner of the map area some of the sediment included within the Sand River Formation was deposited much earlier.

Nature of contacts

Lower contact

In a few places within the uplands in the southeast, silt and clay of the Ethel Lake Formation rest on an oxidized surface of the Bonnyville Formation, indicating a disconformable contact (figure 9, cross section E1-E1', test hole T41). In most places this contact is sharp and nongradational. The contact is sharp in the Kehiwin Plateau and the Beaver Lowlands where sand and gravel of the Ethel Lake Formation overlie the Bonnyville till.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Tp
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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
570
560
550
520
510
600
Silt and Clay
Sand and Silt
Sand and Gravel
Clay, Silt, Sand, and Gravel
0
10
km
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Unit Boundaries:
Approximate
Assumed
Contours, Interval 10 metres:
Defined
Approximate
500
Data Location

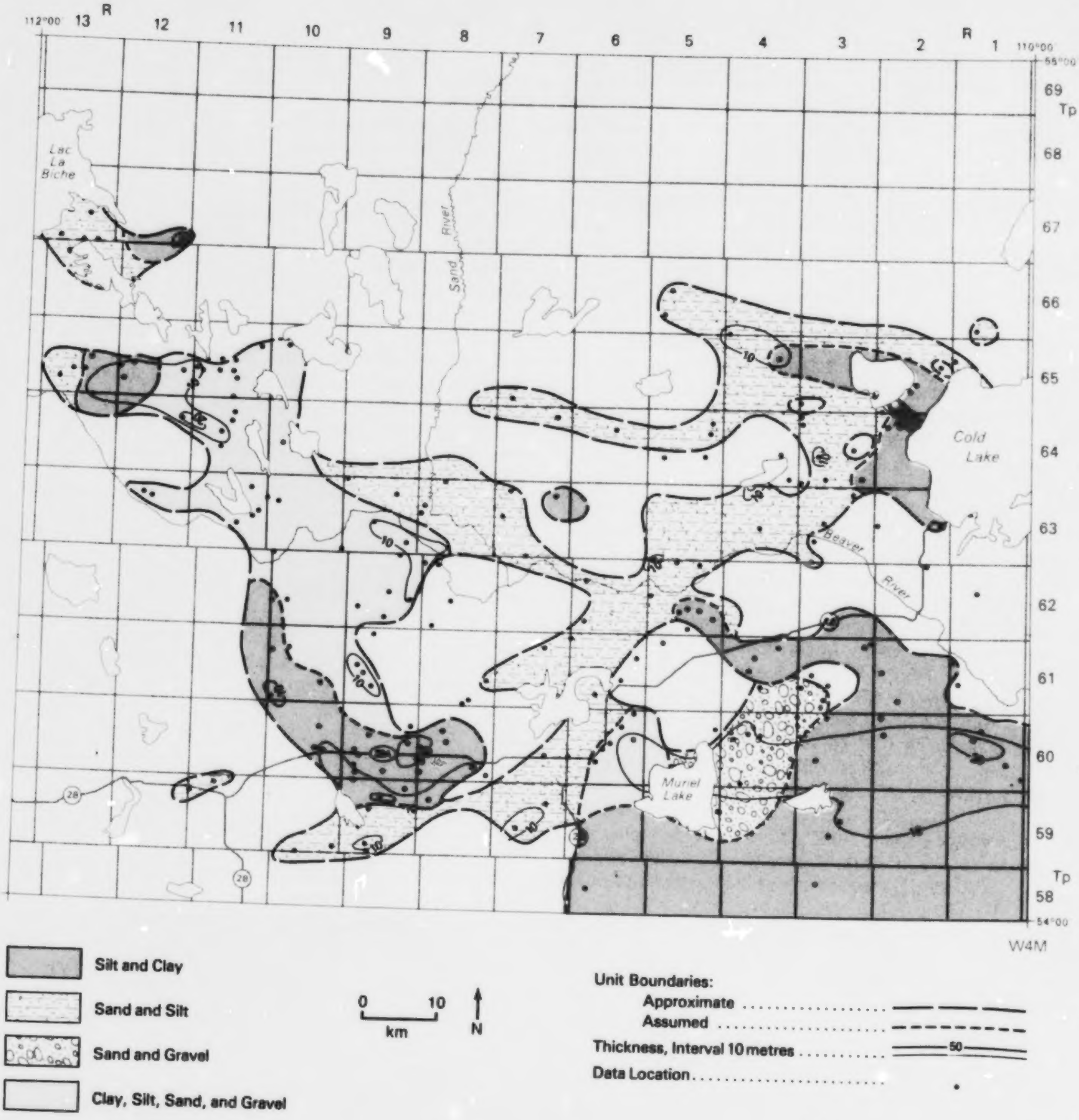
Figure 33. Elevation of the upper surface of the Ethel Lake Formation. Note the sporadic distribution of the formation in the east-central part of the map area.

Upper contact

Silt and clay of the Ethel Lake Formation commonly have a gradational contact with the base of the Marie Creek Formation (Andriashek and Fenton 1979, test holes T13B and T15). As discussed in the following description of the Marie Creek Formation, this reflects glacial erosion of the top of the Ethel Lake Formation. Coarser sand and gravel of the Ethel Lake Formation generally have a much sharper contact with the base of the Marie Creek Formation.

Origin of the sediment in the Ethel Lake Formation

On the basis of geographic distribution and thickness, sand and gravel of the Ethel Lake Formation in the north end of the Kehiwin Plateau and Beaver Lowlands are probably of glaciofluvial origin. Figures 29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54°00
W4M
Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
10
Silt and Clay
Sand and Silt
Sand and Gravel
Clay, Silt, Sand, and Gravel
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 34. Thickness of clay, silt, sand, and gravel in the Ethel Lake Formation. Note the predominance of thick silt and clay along the southern and southwestern boundary of the formation.

and 33 show that this coarser-grained material lies within a poorly defined drainage basin that developed on the surface of the underlying Bonnyville Formation. The thinness of the Bonnyville Formation in this drainage basin indicates that the till was eroded by the same meltwater that deposited the sand and gravel.

Silt and clay of the Ethel Lake Formation are interpreted to have a glaciolacustrine origin, deposited from proglacial lakes that formed during the advance of the third known glaciation in the area, here named the Ardmore Glaciation. Evidence to support a lacustrine origin includes auger samples with finely bedded or rhythmically bedded structures in places. These finely bedded deposits are generally thick, locally thicker than 5 m, which indicates deposition in calm water near a glacial margin. The wide distribution of the silt and clay, both on the uplands and in the lowlands, also supports deposition from a proglacial lake.

Most of the sediment deposited within these proglacial lakes was probably derived from meltwater flowing from the Ardmore Glacier as well as from the regional northeast drainage that ponded against the ice margin. The curved northwest-southeast configuration of thick deposits of the Ethel Lake Formation (figure 33) probably reflects deposition along an ice-lobe margin.

Lithologic differences in sediment of the Ethel Lake Formation probably reflect differences in distance from source. East of Reita Lake, Tp 59, R 3, the formation consists almost entirely of silt and clay with only a small amount of sand or gravel. The predominance of fine sediment indicates that the source of meltwater was a more distant ice margin to the north. As this margin advanced southwest, the lake level rose along the regional north-facing slope of the Reita Upland, ultimately depositing silt and clay at an elevation at least 90 m higher than the silt and clay in the Beaver Lowlands. Farther southwest, sand and gravel were interbedded with or deposited on the silt and clay (figure 10, cross section N1-N1', test holes E966 and E1723). This sequence is interpreted as deposition in a fluctuating glaciofluvial and glaciolacustrine environment, possibly in an ice-contact delta along the northeast margin of the lake.

The absence of a weathered zone in the upper part of the Ethel Lake Formation indicates either that a weathered surface may have once been present but was later eroded during the Ardmore Glaciation, or that the formation was buried by till very soon after it was deposited and was never exposed. As discussed in the following chapter, the overlying Marie Creek till contains eroded and incorporated clasts of unoxidized silt and clay of the Ethel Lake Formation. This is given as evidence that the original surface of the Ethel Lake Formation was never exposed to weathering.

Marie Creek Formation

Source of name: Marie Creek, Alberta, located in the eastern part of the Sand River map area, NTS 73L.
Type section: Alberta Geological Survey auger test hole T9, located along the Beaver River in LSD 13, Sec 10, Tp 62, R 2, W 4 Mer within the Sand River map area, NTS 73L (figure 35).
Type area: The area northwest of the town of Grand Centre in the eastern part of the Sand River map area, NTS 73L.
Reference sections: Outcrops LA81-1 (LSD 1, Sec 30, Tp 63, R 2, W 4 Mer), and SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer) located along the Marie Creek; Alberta Geological Survey auger test holes T6 (LSD 16, Sec 31, Tp 62, R 3, W 4 Mer), T13B (LSD 1, Sec 30, Tp 60, R 2, W 4 Mer), and T32 (LSD 12, Sec 1, Tp 64, R 3, W 4 Mer); Alberta Environment test holes E802 (LSD 5, Sec 32, Tp 61, R 5, W 4 Mer), and E1712 (LSD 1, Sec 11, Tp 62, R 5, W 4 Mer).

Description of formation

The Marie Creek Formation consists of diamicton that is characterized by the following: a large amount of calcareous material, particularly dolostone in the very-coarse-sand fraction, and dolomite in the silt-clay fraction; a large amount of very coarse sand; and a high resistivity (table 2). The upper part of the formation, both in outcrop and subsurface, is commonly olive brown whereas the lower part is dark gray.

The Marie Creek Formation is widespread but does not cover all of the Sand River map area. Only the upper part of the formation outcrops, mainly along stream and road cuts. The entire formation has been mapped in the subsurface from auger samples, rotary-drill cuttings, sidewall samples, and geophysical logs. On the basis of grain size of the smaller-than-2-mm fraction, the formation is divided into two units: unit 1, consisting of clayey diamicton, which is overlain by unit 2, consisting of sandy diamicton. Each is described separately below.

Unit 1

Description of unit

Unit 1 has been mapped from auger samples and electric logs only. It consists of dark gray (5Y 4/1) sandy-clay diamicton. The grain size of the smaller-than-2-mm fraction averages about 32% sand, 30% silt, and 38% clay; this includes 2.0% very coarse sand (figure 18). The range in grain size is shown in table 5. In many auger samples, lenses or attenuated clasts of silt and clay are found, confined to thin layers or streaks within the diamicton. In places these streaks of silt and clay are imbedded in a more sandy diamicton, similar to that of the overlying unit 2 of the Marie Creek Formation. The moisture content of unit 1 is about 11%, which is slightly greater than that for unit 2.

The very-coarse-sand fraction of unit 1 averages about 62% igneous and metamorphic rock, 27% quartz, 3% limestone, 6% dolostone, less than 1% quartzite and quartz sandstone, and less than 2% local rock (figure 18). The range in sand composition is shown in table 5 (appendix B).

Calcareous material makes up 12 to 17% of the silt-clay fraction (calcite/dolomite ratio = 0.25, figure 18).

The clay minerals of a few representative samples consist of about 45 to 55% illite, 25% kaolinite, 15 to 25% smectite, and 5% chlorite (appendix C).

Distribution, thickness, and subcrop topography

Unit 1 of the Marie Creek Formation is confined mainly to the Beaver Lowlands and the Reita Upland (figure 36). It extends in a lobe form southwest as far as Tp 59, R 10, following a shallow depression on the surface of the underlying Ethel Lake Formation (figure 33). Smaller areas of unit 1 have been mapped above segments of the buried Helina Valley in the northwest, but the extent of these is not well known. The unit ranges in elevation from as high as 620 m within the Reita Upland in the southeast and the Lac La Biche Upland in the southwest, to as low as 500 m within a small valley south of Cold Lake (figure 36).

Unit 1 is generally thin within the map area, particularly within the Beaver Lowlands and Reita Upland where commonly it is less than 5 m thick. It is thickest within the Kehiwin Plateau in the southwest, where as much as 25 m are present (figure 37).

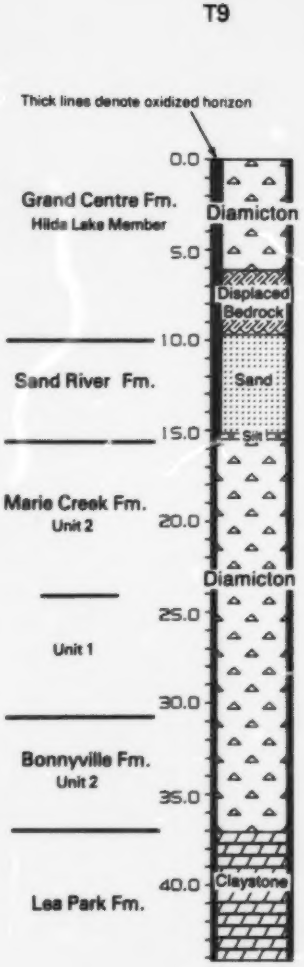
Differentiation from other units

Unit 1 is differentiated from unit 2 of the Marie Creek Formation mainly on the basis of grain size. Unit 1 is more clayey and commonly contains lenses and partings of silt and clay. Both units have similar very-coarse-sand compositions except that unit 1 does not contain the very high dolomitic facies like that found at the top of unit 2 (figure 18). It may be more appropriate to consider the clayey unit 1 as a grain-size facies of the sandier unit 2 of the formation because silt and clay lenses and partings in unit 1 are commonly imbedded in an otherwise sandy diamicton, similar to the diamicton of unit 2. However, the distribution and thickness of unit 1 can be mapped over a wide area, and its differentiation from unit 2 is not only easily made but also useful for characterizing and correlating the Marie Creek Formation throughout the map area.

Unit 1 is differentiated from the underlying Bonnyville till mainly on the basis of the very-coarse-sand

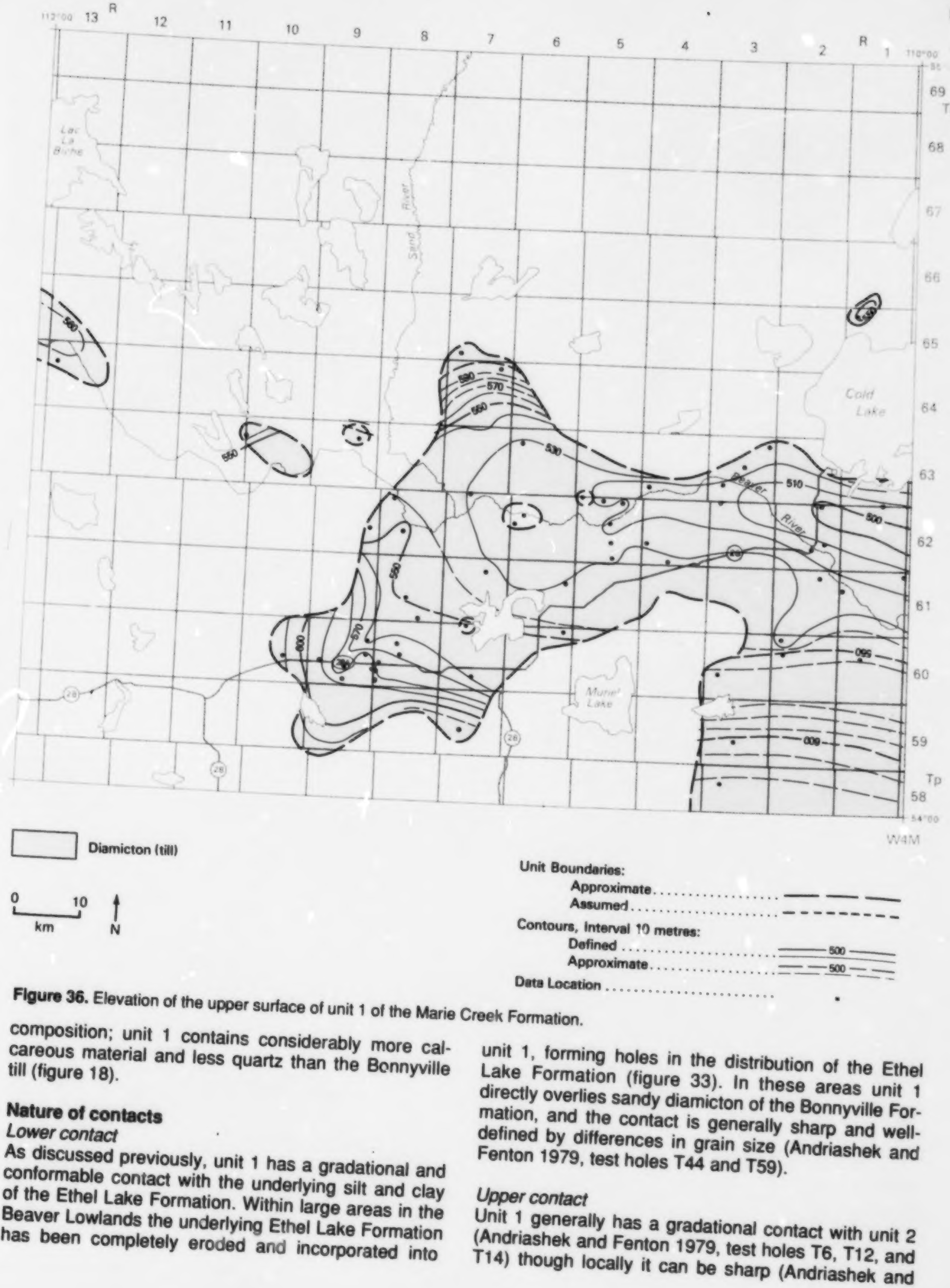
Alberta Geological Survey test hole: T9
Location: SE of LSD 13 Sec 10 Tp 62 R 2 W 4 M NTS:73L

Elevation: 1775 ft, 541 m
Date drilled: July 9, 1976 Logged by: L. Andriashek.


T9
Thick lines denote oxidized horizon
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Grand Centre Fm.
Hilda Lake Member
Sand River Fm.
Marie Creek Fm.
Unit 2
Unit 1
Bonnyville Fm.
Unit 2
Lea Park Fm.
Diamicton
Displaced Bedrock
Sand
Silt
Diamicton
Claystone

Depth (m)	Grain Size Properties: Sand % >62.5µm	Silt %	Clay % <4µm	1-2 mm Sand %	Moisture %	Silt and Clay Carbonate Content: CO₂ (cm³)	CO₃ %	Calcite/Dolomite	1-2 mm Sand Petrology: Igneous Metamorphic %	Quartz %	Quartzite Quartz Sandstone %	Limestone %	Dolostone %	Local %	Other	Total number of grains
2	9	19	73	0.4	20				68	21	0	0	0	11	0	57
3	26	29	46	0.2	13				78	15	1	2	3	1	0	151
5	28	27	45	1.4	13				65	29	1	2	2	2	0	187
6	4	41	54	0.1	15											
8	2	48	50	0.2	15											
9	4	34	62	0.3	16											
17	40	33	27	3.1	9				57	19	0	4	14	4	0	396
18	42	31	28	3.6	9				59	21	1	3	16	6	0	328
20	39	33	28	2.8	9				65	16	0	3	14	2	0	365
22	46	26	28	2.8	10				61	27	1	2	8	2	0	329
23	41	26	33	3.5	9				74	18	0	2	4	2	0	457
24	35	31	34	2.2	10				68	26	0	2	3	0	0	300
26	32	34	34	2.2	10				64	25	2	3	5	2	0	292
27	32	33	35	2.2	10				66	25	0	4	4	1	0	287
28	28	32	40	2.0	11				63	28	0	4	4	2	0	283
31	48	29	24	3.1	9				63	27	0	2	6	2	0	385
32	48	29	23	3.0	9				58	29	1	5	5	2	0	413
33	42	28	30	2.4	9				61	28	2	5	1	4	0	324
34	40	30	30	2.7	10				53	34	3	7	2	2	0	351
35	42	27	31	3.0	8				61	30	2	3	2	2	0	390
36	39	30	32	2.9	10				58	33	1	6	2	1	0	379
40					15											
42					15											
44																

Figure 35. Type section of the Marie Creek Formation and Sand River Formation. Alberta Geological Survey test hole T9.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Sand River
Cold Lake
Beaver River
Muriel Lake
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560
600
Diamicton (till)
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10
km
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Unit Boundaries:
Approximate
Assumed
Contours, Interval 10 metres:
Defined
500
Approximate
500
Data Location

Figure 36. Elevation of the upper surface of unit 1 of the Marie Creek Formation.

composition; unit 1 contains considerably more calcareous material and less quartz than the Bonnyville till (figure 18).

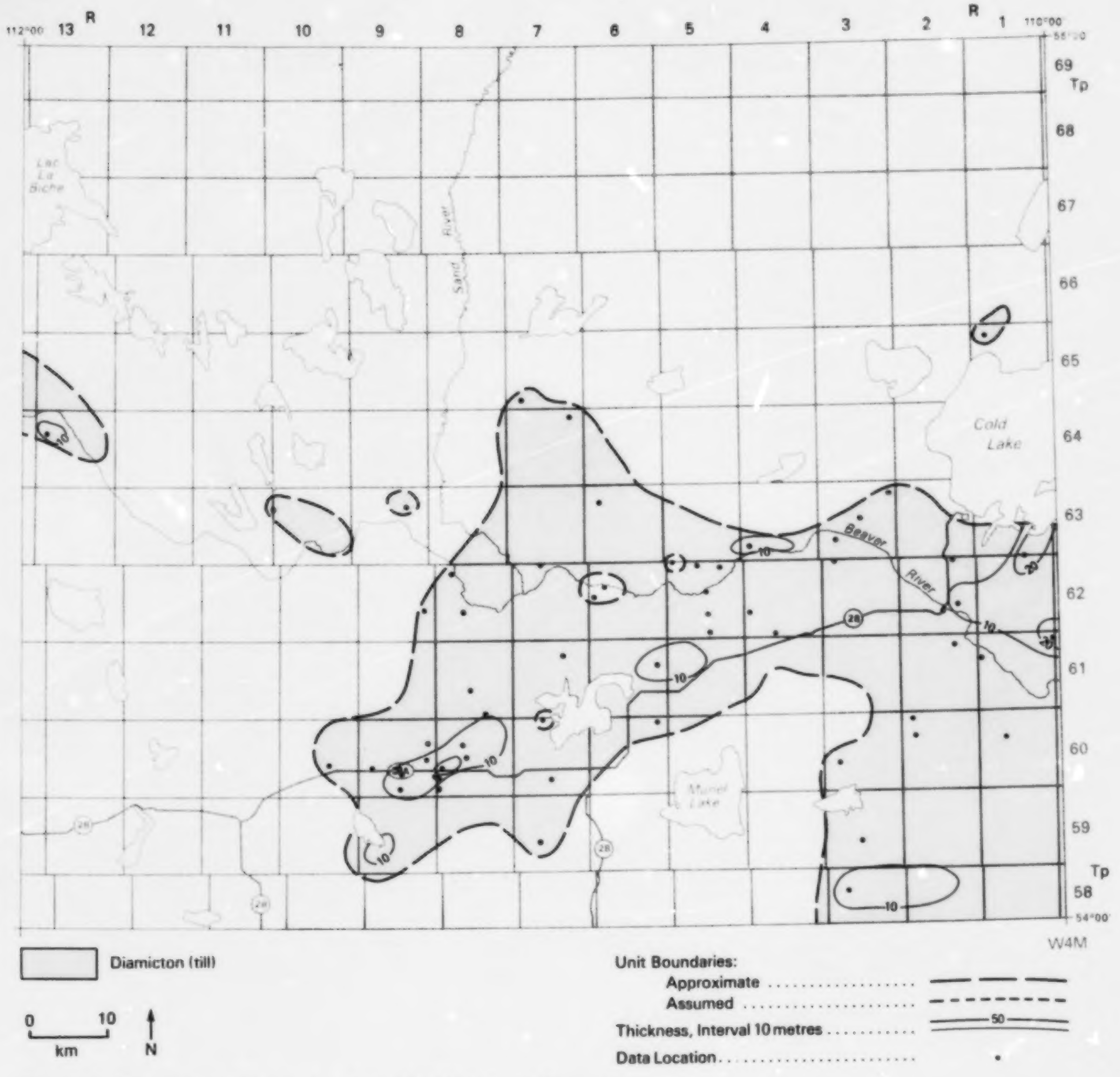
Nature of contacts

Lower contact

As discussed previously, unit 1 has a gradational and conformable contact with the underlying silt and clay of the Ethel Lake Formation. Within large areas in the Beaver Lowlands the underlying Ethel Lake Formation has been completely eroded and incorporated into unit 1, forming holes in the distribution of the Ethel Lake Formation (figure 33). In these areas unit 1 directly overlies sandy diamicton of the Bonnyville Formation, and the contact is generally sharp and well-defined by differences in grain size (Andriashek and Fenton 1979, test holes T44 and T59).

Upper contact

Unit 1 generally has a gradational contact with unit 2 (Andriashek and Fenton 1979, test holes T6, T12, and T14) though locally it can be sharp (Andriashek and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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
10
Diamicton (till)
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10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 37. Thickness of diamicton in unit 1 of the Marie Creek Formation.

Fenton 1979, test hole T3). In the field, the contact is commonly recognized within the auger samples at the first occurrence of silt and clay layers within the diamicton. In this study, however, the top of unit 1 is defined from the analytical values, generally at the depth where the amount of clay exceeds the amount of sand in the diamicton.

Unit 2

Description of unit

Unit 2 of the Marie Creek Formation is widespread in the Sand River map area. It is characterized by sandy diamicton, the top of which in many places is weathered and oxidized olive (5Y 4/4) to olive brown (2.5Y 4/4). This oxidized zone has been mapped both in outcrop and within test holes, buried at depths as much as 35 m (plate 1; and Andriashek and Fenton 1979, test hole T7). Samples from outcrops show that the oxidation is not confined to joint surfaces, but pervades the sediment (plates 1 and 2). Below this oxidized zone the diamicton is dark gray (5Y 4/1).

The upper part of the oxidized zone is commonly highly jointed, forming angular joint blocks about 6 cm in length, 3 cm in width, and 2 cm in thickness (plate 2). Iron oxide or manganese oxide stain is present

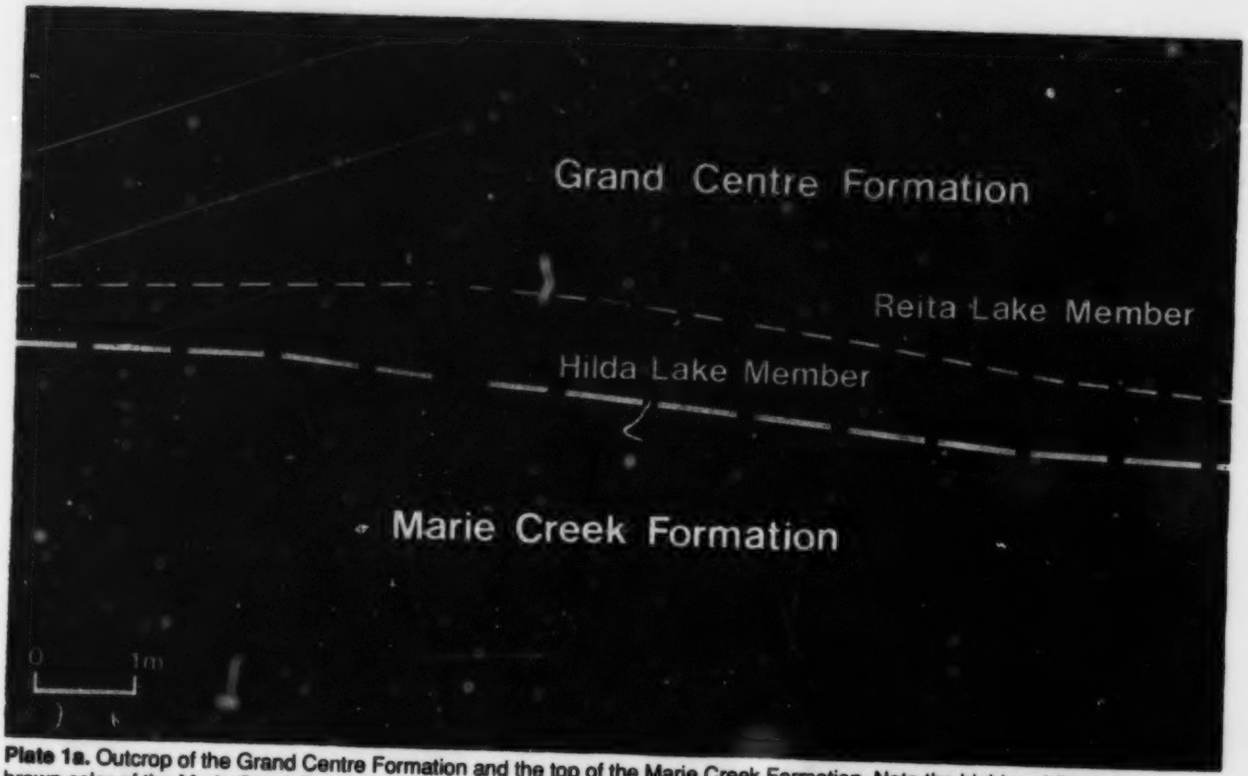
Grand Centre Formation
Reita Lake Member
Hilda Lake Member
Marie Creek Formation
0
1m

Plate 1a. Outcrop of the Grand Centre Formation and the top of the Marie Creek Formation. Note the highly oxidized olive brown color of the Marie Creek Formation. Section LA 81-1 (LSD 1, Sec 30, Tp 63, R 2, W 4 Mer). View looking north.

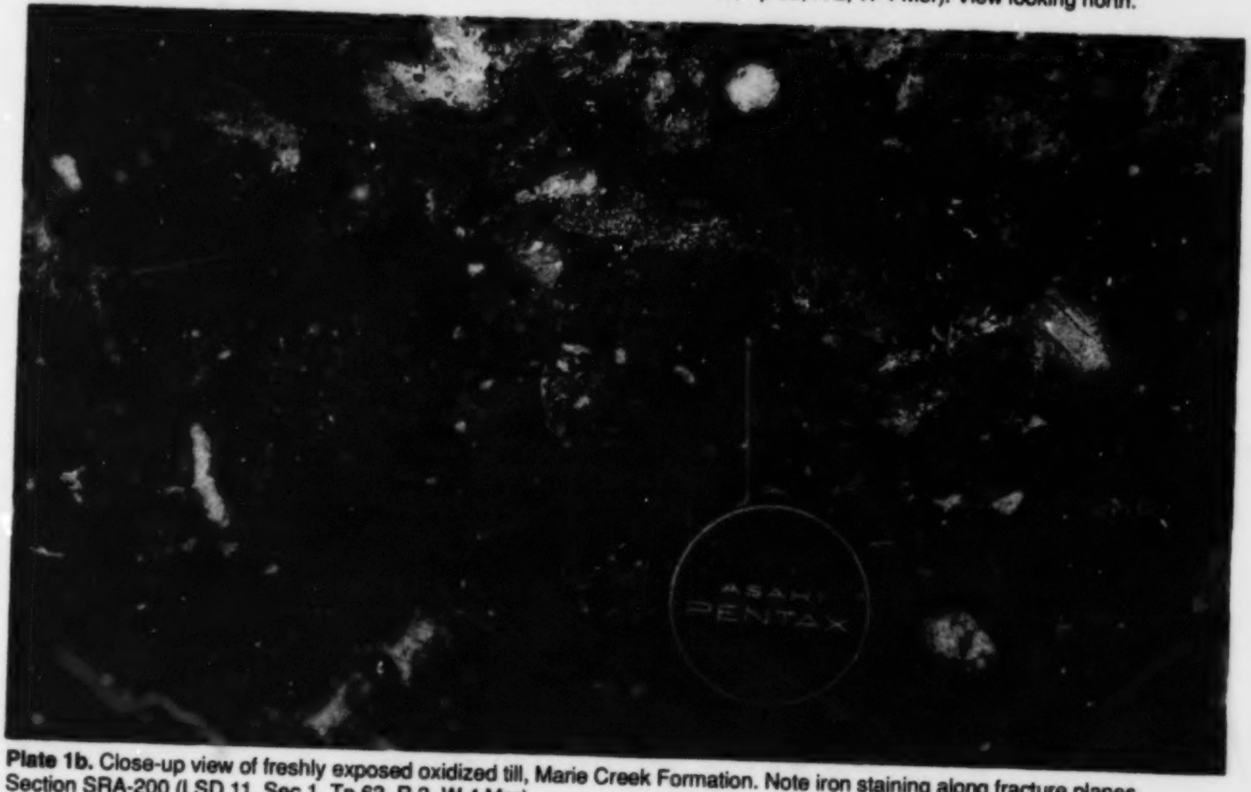
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Plate 1b. Close-up view of freshly exposed oxidized till, Marie Creek Formation. Note iron staining along fracture planes. Section SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer).

Plate 2a. Blocky, fractured structure of the till in the upper, oxidized portion of the Marie Creek Formation. Section SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer).

Plate 2b. Iron staining along widely spaced joints in till of the lower, unoxidized portion of the Marie Creek Formation. Section SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer).

along the joint surfaces and fracture planes (plates 1 and 2). The degree of jointing decreases downward; only widely spaced joints, spaced a few metres apart, are present at depth. The fracturing, combined with the sandiness of the unit, results in the upper part being easy to excavate with a pick or backhoe, even though the formation as a whole is very dense.

In some places a concentration of boulders is recognized at the contact between unit 2 and the overlying Grand Centre Formation (plate 3). It is uncertain to which of the formations the boulder concentration belongs. In section SRA-200, located in LSD 11, Sec 1, Tp 63, R 3, W 4 Mer, a boulder concentration also occurs within the Marie Creek Formation (plate 3), indicating that more than one boulder concentration is associated with unit 2.

Numerous sand and gravelly sand lenses occur within unit 2 along Marie Creek in the east. In section SRA-200, these lenses are so numerous as to produce a poorly stratified appearance in the outcrop (plate 4). These lenses range in length from centimetres to metres and are about 15 to 20 cm thick. Typically most of the lenses are horizontally or nearly horizontally bedded. The extent of these lenses beyond the Marie Creek area is unknown because of few exposures.

The diamicton of unit 2 characteristically contains abundant granules, pebbles, and very coarse sand (2.7%, figure 18). The grain size of the smaller-than-2-mm fraction of the diamicton averages about 41% sand, 30% silt, and 29% clay (figure 18). The range in grain size is shown in table 6 (appendix B). The sandiness and denseness of unit 2 results in a low moisture content of about 9 to 10%. This causes the upper part of unit 2 to be difficult to penetrate with an auger.

The very coarse sand averages about 61% igneous and metamorphic rock, 21% quartz, 4% limestone, 13% dolostone, less than 1% quartzite and quartz sandstone, and 1 to 2% local rock (figure 18). The range in composition is shown in table 6 (appendix B).

Calcareous material makes up as much as 20% of the silt-clay fraction (calcite/dolomite ratio = 0.17, figure 18). On the basis of carbonate content, unit 2 can be divided into two facies: (1) an upper facies that contains abundant dolostone in the very-coarse-sand fraction and abundant dolomite in the silt-clay fraction; (2) a lower facies that contains less calcareous material, but more than in the diamictons of other formations (figure 18; and table 6, appendix B).

The clay minerals of a few representative samples of unit 2 consist of about 50 to 60% illite, 20 to 25% kaolinite, 15 to 20% smectite, and 5 to 10% chlorite (appendix C).

The top of unit 2 has a distinctly higher resistivity compared to the base of the overlying Grand Centre Formation (figure 12). This probably results from the combined effects of the fractured, oxidized zone, the abundant sand, the low moisture content, and the abundant carbonate at the top of unit 2.

Distribution, thickness, and subcrop topography

Unit 2 is widespread in the eastern half and central parts of the Sand River map area but is not recognized in the southwest or northwest regions (figure 38). It probably once was present in the northwest but was eroded by the last glaciation in the area. The evidence for this is given in the following section, a discussion of the differentiation of the Marie Creek and Grand Centre formations. The southwest limit of unit 2 is defined by a northwest-southeast trending margin that extends from Tp 65, R 13 to Tp 58, R 7. Along this margin, unit 2 terminates against the northeast flank of the underlying upland, except for a small lobe that extends southwest along a shallow depression above the buried Beverly Valley in Tp 58-59, R 9-11 (figure 38). The northern extent is uncertain because data are lacking.

The elevation of unit 2 ranges from as high as 640 m within the Reita and Marguerite uplands to as low as 510 m along the Beaver Lowlands in Tp 63, R 3-4 (figure 38). The unit is between 10 and 20 m thick over much of its extent (figure 39). Exceptions to this are a number of thin areas (0 to 9 m) in the Beaver Lowlands. One such area extends northward from Muriel Lake in Tp 59, R 6, to Marie Lake in Tp 64, R 2; the other follows the base of the scarp along the south edge of the Marguerite Upland in Tp 64, R 2-7. The thickest parts of unit 2 are in the Reita and Marguerite uplands where as much as 47 m have been mapped (figure 9, cross section E2-E2'; and figure 39).

Because unit 1 of the Marie Creek Formation is thin in most places the total thickness of the formation does not differ much from that of unit 2 (figures 39 and 40). An exception is in Tp 61-63, R 2-6 where both units are thick within a valley that was incised into the surface of the underlying Bonnyville Formation (see figure 29).

Differentiation from other units

Unit 2 is differentiated from all other units by its abundant carbonate content, particularly dolomite. In the east, where unit 2 of the Marie Creek Formation and unit 2 of the Bonnyville Formation are both sandy, the two are differentiated by the abundance of dolostone and paucity of quartz in the Marie Creek Formation (figure 18). Unit 2 of the Marie Creek Formation is generally dense and more difficult to drill compared to the Bonnyville Formation.

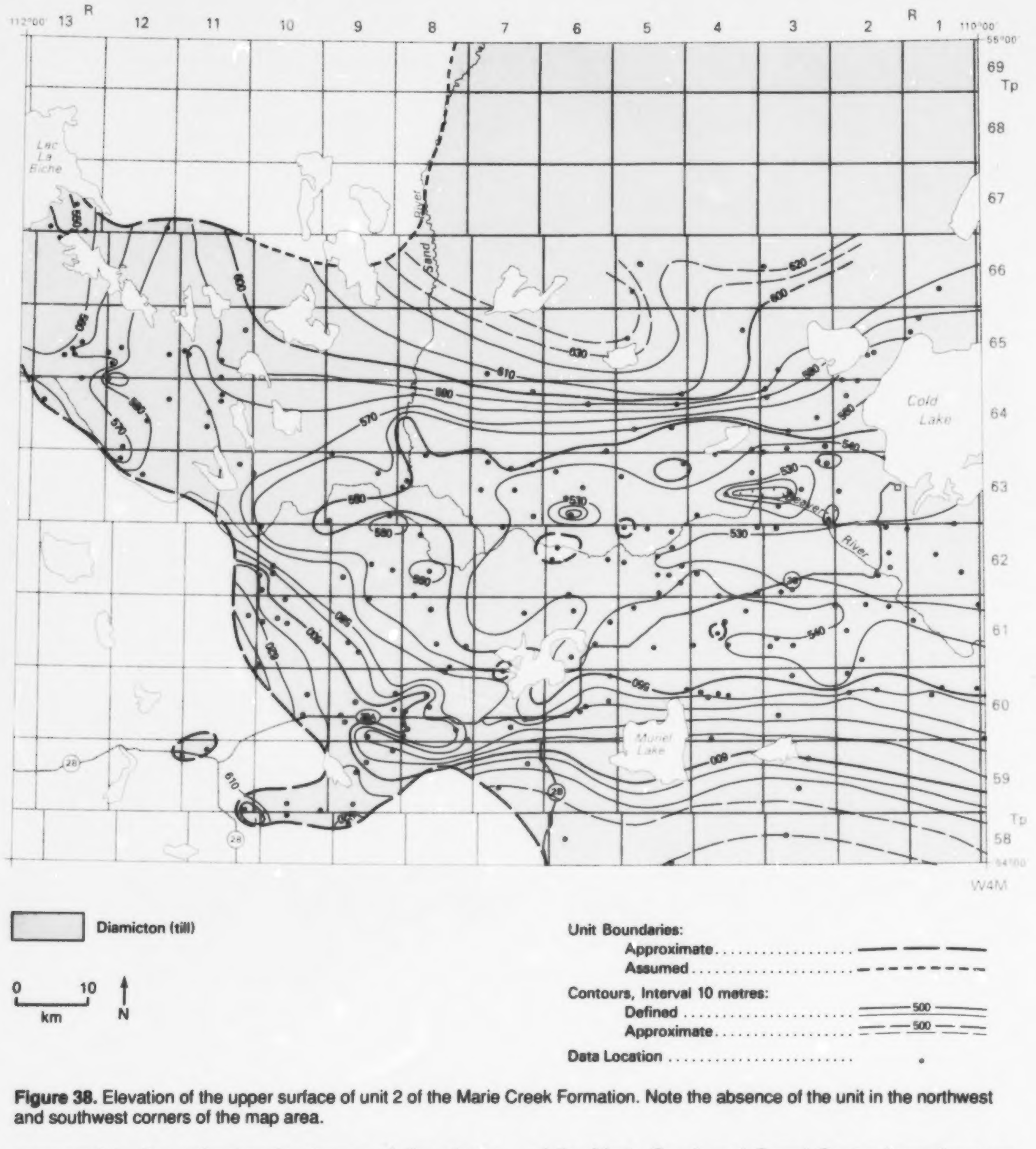
Unit 2 of the Marie Creek Formation is differentiated from the various members of the overlying Grand Centre Formation by its color, structure, grain size, lithic composition, and resistivity. The top of unit 2 generally is more olive brown, in contrast to the dark gray brown of the Grand Centre Formation (plate 4). The upper part of unit 2 is commonly highly fractured

Plate 3a. Boulder concentration along the contact of the Grand Centre Formation and Marie Creek Formation. Section LA81-1 (LSD 16, Sec 19, Tp 63, R 2, W 4 Mer).

Plate 3b. Boulder concentration within the Marie Creek Formation. Section SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer).

Plate 4a. Nearly horizontal lenses of sand interbedded with diamicton, Marie Creek Formation. Section SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer).

Plate 4b. Irregularly shaped inclined lenses of sand within diamicton of the Marie Creek Formation. Section SRA-200 (LSD 11, Sec 1, Tp 63, R 3, W 4 Mer).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Muriel Lake
Sand River
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Diamicton (till)
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Unit Boundaries:
Approximate
Assumed
Contours, Interval 10 metres:
Defined
500
Approximate
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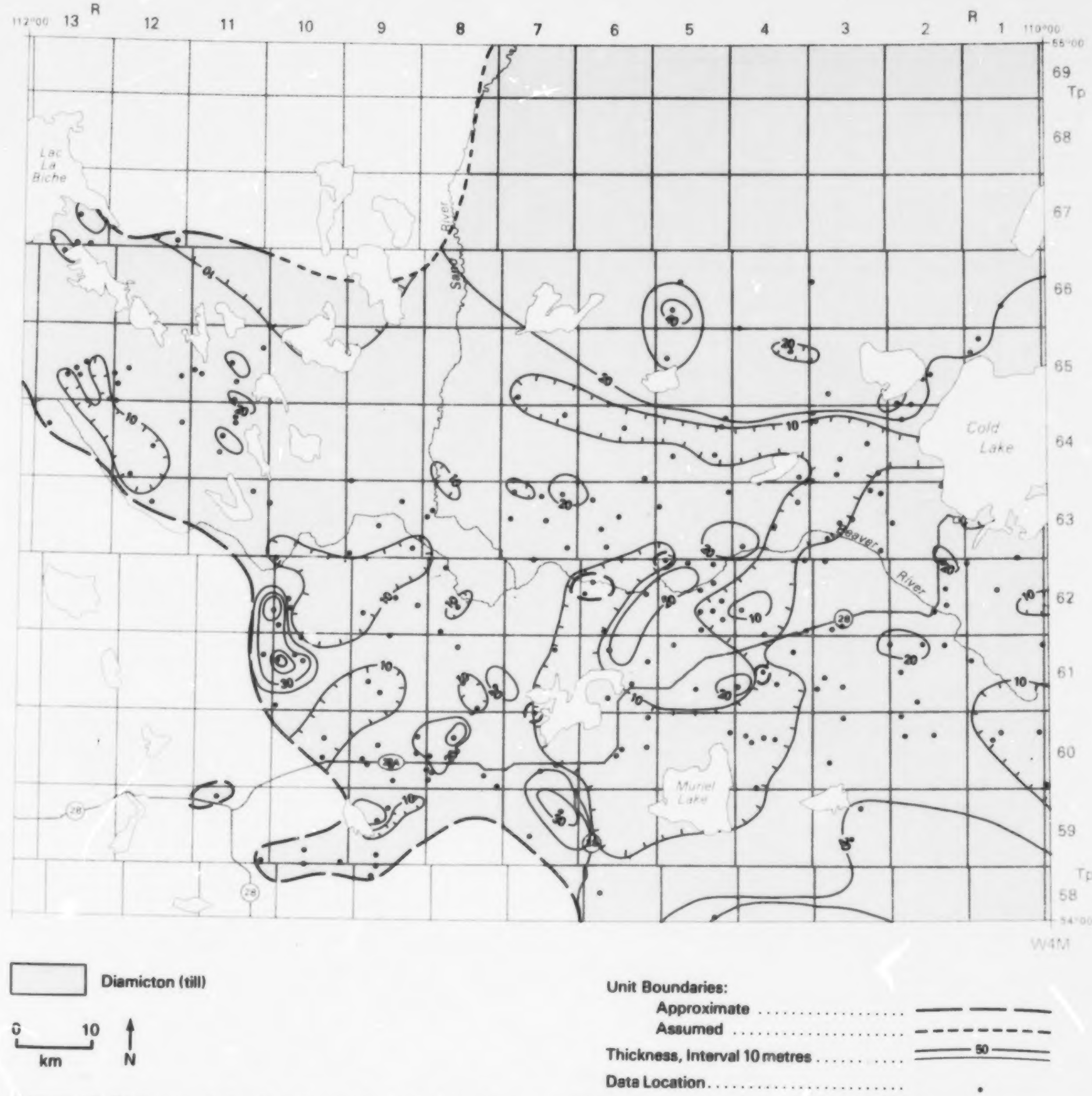
Data Location

Figure 38. Elevation of the upper surface of unit 2 of the Marie Creek Formation. Note the absence of the unit in the northwest and southwest corners of the map area.

compared to the unfractured outcrops of the clayey members of the Grand Centre Formation. Unit 2 is more sandy than most of the members of the Grand Centre Formation, particularly in the amount of very-coarse-sand (figure 18). This abundance of very-coarse-sand permits unit 2 to be differentiated in the field, even in those areas where the overall grain sizes of the Marie Creek and Grand Centre formations are similar (Andriashek and Fenton 1979, test hole T16). Unit 2 contains more dolostone and less igneous and metamorphic rock in the very-coarse-sand fraction and more dolomite in the silt-clay fraction than the Grand Centre Formation (figure 18). Almost everywhere the top of unit 2 has a greater electrical resistance than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Sand River
Cold Lake
Beaver River
Muriel Lake
10
20
30
Diamicton (till)
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 39. Thickness of diamicton in unit 2 of the Marie Creek Formation. Note the isolated areas of thick deposits along the southwest boundary of the unit.

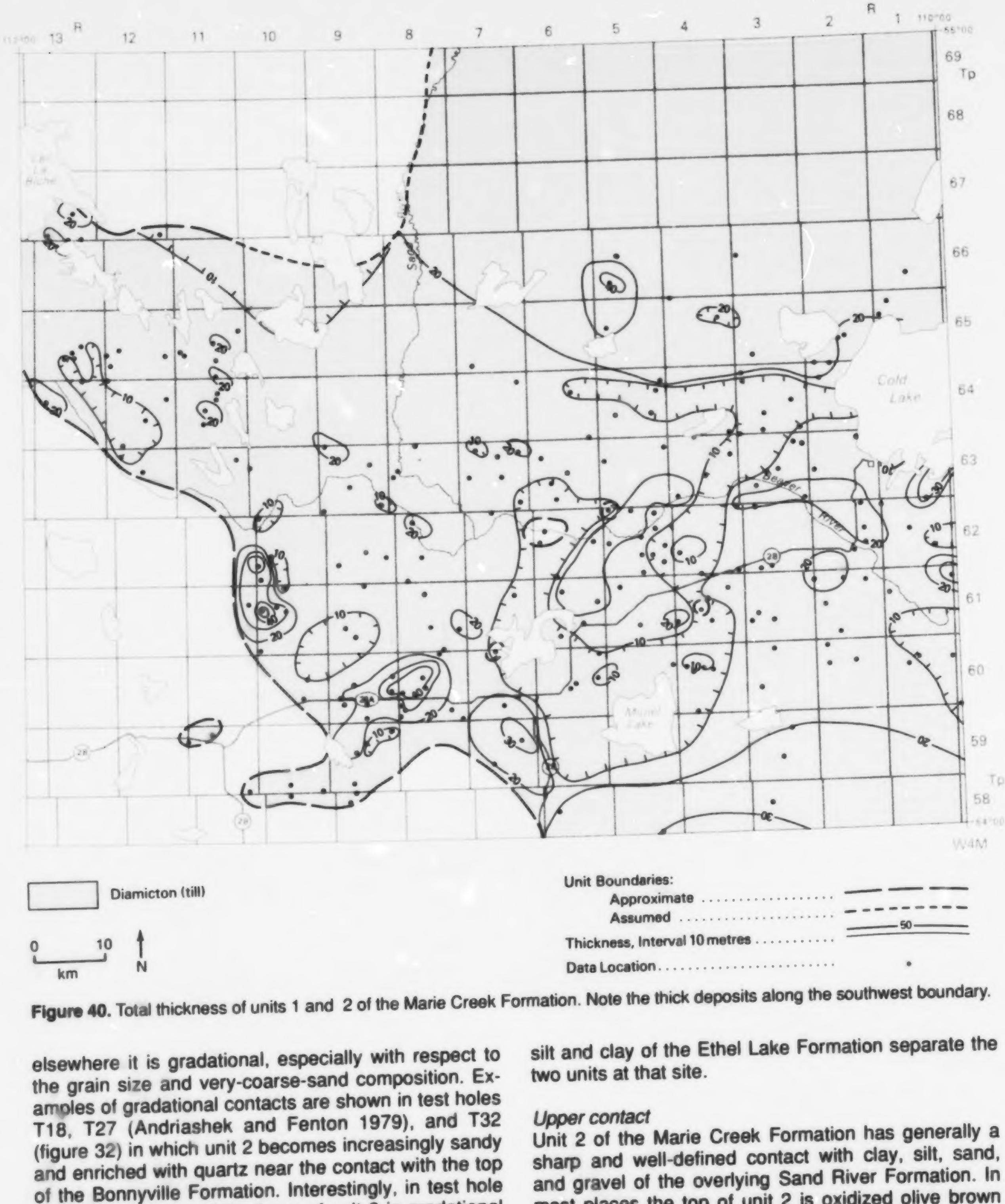
the base of the overlying Grand Centre Formation (figure 12).

In the western part of the map area the differentiation between unit 2 of the Marie Creek Formation and the Grand Centre Formation is more difficult mainly because the distinctive sandy and calcareous upper facies of unit 2 is absent, in part due to glacial erosion. Evidence for glacial erosion is the presence of slabs of the dolomitic facies of unit 2 that are found as displaced blocks in the overlying Vilna Member (figure 10, cross section N1-N1', test hole 77SR12; and Andriashek and Fenton 1979).

Nature of contacts

Lower contact

The contact between the Marie Creek and Ethel Lake formations has been previously discussed. Where unit 2 of the Marie Creek Formation directly overlies the Bonnyville Formation, the contact is varied: in places it is sharp and easily recognized on the resistivity logs;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W4M
Lac La Biche
Cold Lake
Beaver River
Muriel Lake
28
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20
30
40
Diamicton (till)
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 40. Total thickness of units 1 and 2 of the Marie Creek Formation. Note the thick deposits along the southwest boundary.

elsewhere it is gradational, especially with respect to the grain size and very-coarse-sand composition. Examples of gradational contacts are shown in test holes T18, T27 (Andriashek and Fenton 1979), and T32 (figure 32) in which unit 2 becomes increasingly sandy and enriched with quartz near the contact with the top of the Bonnyville Formation. Interestingly, in test hole T32 the grain size of the base of unit 2 is gradational with the very sandy Bonnyville Formation, even though silt and clay of the Ethel Lake Formation separate the two units at that site.

Upper contact

Unit 2 of the Marie Creek Formation has generally a sharp and well-defined contact with clay, silt, sand, and gravel of the overlying Sand River Formation. In most places the top of unit 2 is oxidized olive brown whereas the base of the Sand River Formation is gray. This probably indicates a disconformable contact.

Field and analytical data show that for the most part the contact between unit 2 of the Marie Creek Formation and the overlying Grand Centre Formation is sharp. In the east, this contact is commonly defined by a boulder concentration (plate 2), though it is uncertain to which unit the boulders belong. Gradational or erosional contacts between the two formations are recognized in two areas. One area is within the eastern part of the Beaver Lowlands where the grain size and sand composition of the Grand Centre Formation are gradational with unit 2 of the Marie Creek Formation (Andriashek and Fenton 1979, test holes T10, T13B, T25, T42, T44, T49, T59, and T73). In this area the contact between the two is generally well defined on the electric logs. The other area is in the west where the sandy, dolomitic facies of unit 2 has been glacially incorporated into the Grand Centre Formation (figure 10, cross section N1-N1', test hole 77SR12).

Origin and differences in the properties of the sediment in the Marie Creek Formation

Both diamicton units of the Marie Creek Formation are tills that were deposited during the third known glaciation in the map area, the Ardmore Glaciation. The abundance of carbonates, particularly dolostone, in the formation indicates that a considerable amount of the Devonian carbonates was eroded compared to the amount for the other formations containing till. This suggests that either more carbonates were exposed to erosion prior to this glacial event, compared to the areas exposed during previous glaciations, or that the Ardmore Glacier travelled parallel to, rather than across, the north-south trend of carbonate outcrops in northeast Alberta (Geological Map of Alberta, Green 1972). Evidence to support this latter hypothesis are the pebble orientations of the upper part of the Marie Creek Formation, measured in a backhoe section at site LA81-2 (figure 41). Here, the pebble fabric shows that in the eastern part of the map area, pebbles have a preferred north-northwest to south-southeast orientation indicating glacial flow from slightly west of north. This flow direction is roughly parallel to the trend of Devonian carbonate outcrops in northeastern Alberta.

The sporadic distribution of the Ethel Lake Formation in the Beaver Lowlands, as well as the widespread distribution of unit 1 of the Marie Creek Formation in the lowlands, are evidence that the clayey till of unit 1 was derived from erosion of the underlying silt and clay of the Ethel Lake Formation (figures 33 and 36). The amount of erosion differed from place to place, accounting for the within-hole and areal differences in the grain-size distribution of unit 1 (figure 42). Some of the clay of unit 1 can also be attributed to incorporation of claystone from the Lea Park Formation. This is shown by the abundance (9%) of claystone in the very-coarse-sand fraction of unit 1 in test hole T3 (Andriashek and Fenton 1979) located south of Cold Lake in Tp 61, R 1.

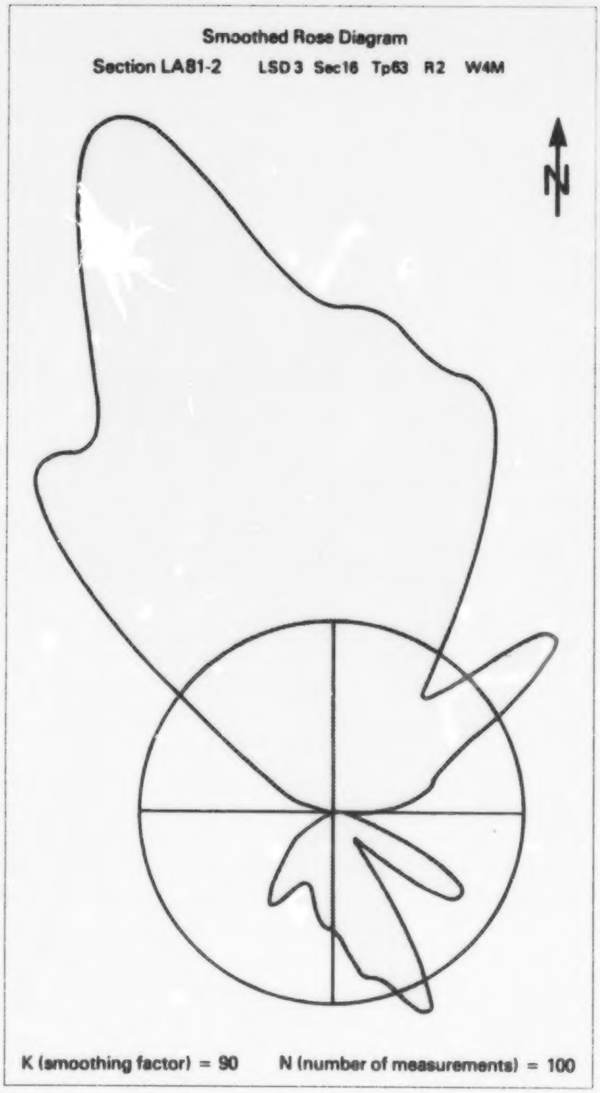
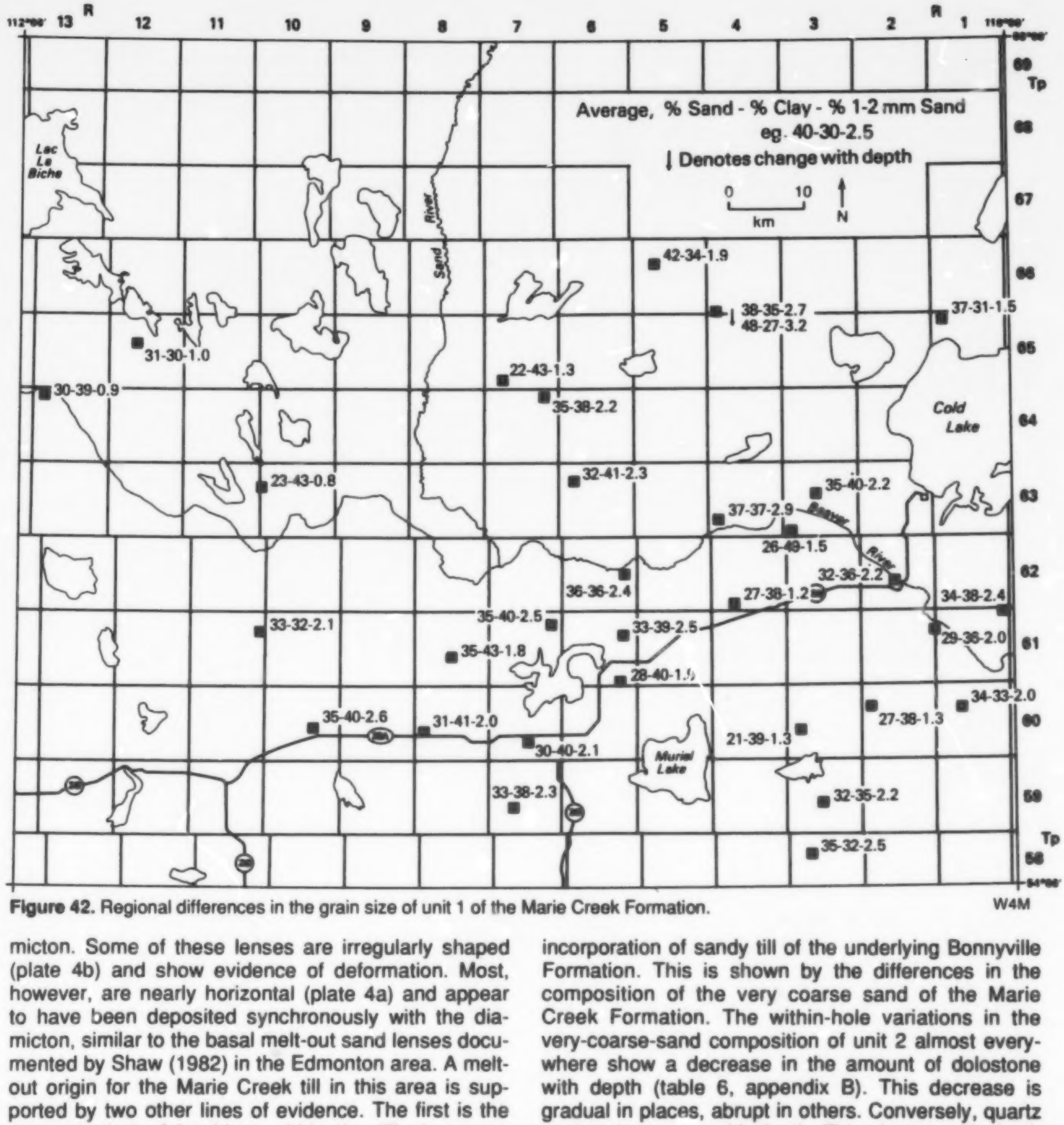


Figure 41. Pebble orientations in the diamicton of unit 2 of the Marie Creek Formation.

Compared to unit 1, unit 2 of the Marie Creek Formation has fewer grain-size differences with depth in given test holes. Consequently the standard deviation about the mean value is generally small, less than 4% in most places (table 6, appendix B). One exception is the eastern part of the map area, along the southern margin of the Marguerite and Medley uplands, where unit 2 becomes significantly more sandy with depth (figure 32). The source of this sand is uncertain, although in section SRA-200, along the Marie Creek, lenses of stratified sand are interbedded with the dia-


Average, % Sand - % Clay - % 1-2 mm Sand
eg. 40-30-2.5
Denotes change with depth
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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
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38-35-2.7
48-27-3.2
37-31-1.5
31-30-1.0
30-39-0.9
22-43-1.3
35-38-2.2
23-43-0.8
32-41-2.3
35-40-2.2
37-37-2.9
26-49-1.5
32-36-2.2
36-36-2.4
27-38-1.2
34-38-2.4
33-32-2.1
35-40-2.5
33-39-2.5
29-36-2.0
35-43-1.8
28-40-1.9
34-33-2.0
35-40-2.6
31-41-2.0
21-39-1.3
27-38-1.3
30-40-2.1
33-38-2.3
32-35-2.2
35-32-2.5

Figure 42. Regional differences in the grain size of unit 1 of the Marie Creek Formation.

micton. Some of these lenses are irregularly shaped (plate 4b) and show evidence of deformation. Most, however, are nearly horizontal (plate 4a) and appear to have been deposited synchronously with the diamicton, similar to the basal melt-out sand lenses documented by Shaw (1982) in the Edmonton area. A melt-out origin for the Marie Creek till in this area is supported by two other lines of evidence. The first is the concentration of boulders within the till at outcrop SRA-200 (plate 3b). These indicate debris bands in the glacier that were preserved by a slow melt-out depositional process. The second type of evidence is the strong preferred pebble fabric at section LA81-2 (figure 41), which probably represents the englacial pebble orientation that was preserved by the melt-out process (Lawson 1979; Shaw 1982).

Another potential source of sand for the Marie Creek till in the eastern part of the map area is glacial incorporation of sandy till of the underlying Bonnyville Formation. This is shown by the differences in the composition of the very coarse sand of the Marie Creek Formation. The within-hole variations in the very-coarse-sand composition of unit 2 almost everywhere show a decrease in the amount of dolostone with depth (table 6, appendix B). This decrease is gradual in places, abrupt in others. Conversely, quartz content increases with depth. This change with depth in the carbonate and quartz content of the very-coarse-sand fraction represents both a slight decrease in the actual amount of carbonates and a slight increase in the actual amount of quartz. The combination of the two yields a significantly lower carbonate-to-quartz ratio for the base of the Marie Creek Formation. This is illustrated in figure 43, in which normalized carbonate (percent carbonate calculated with the exclusion of quartz) is compared to normalized quartz

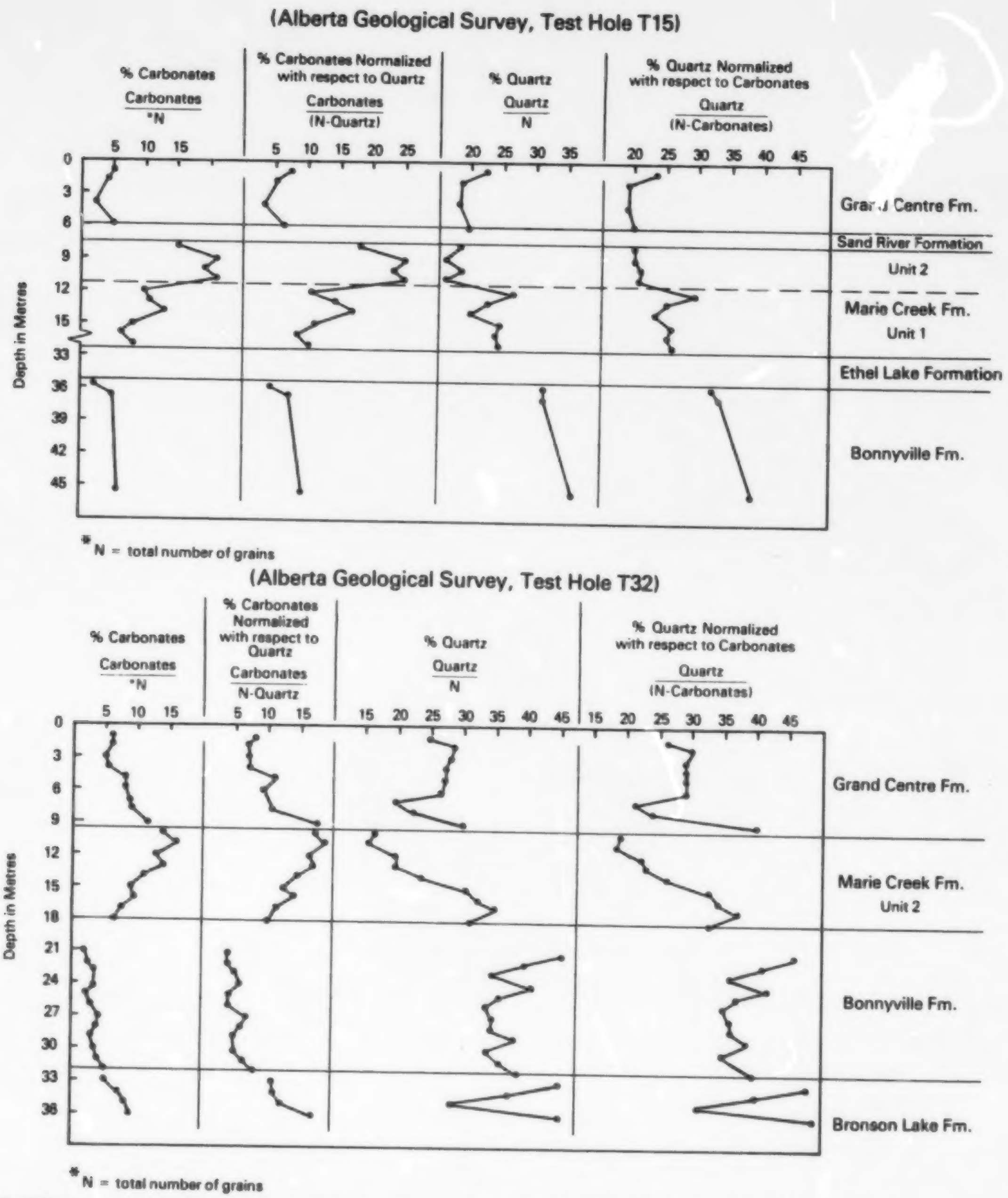
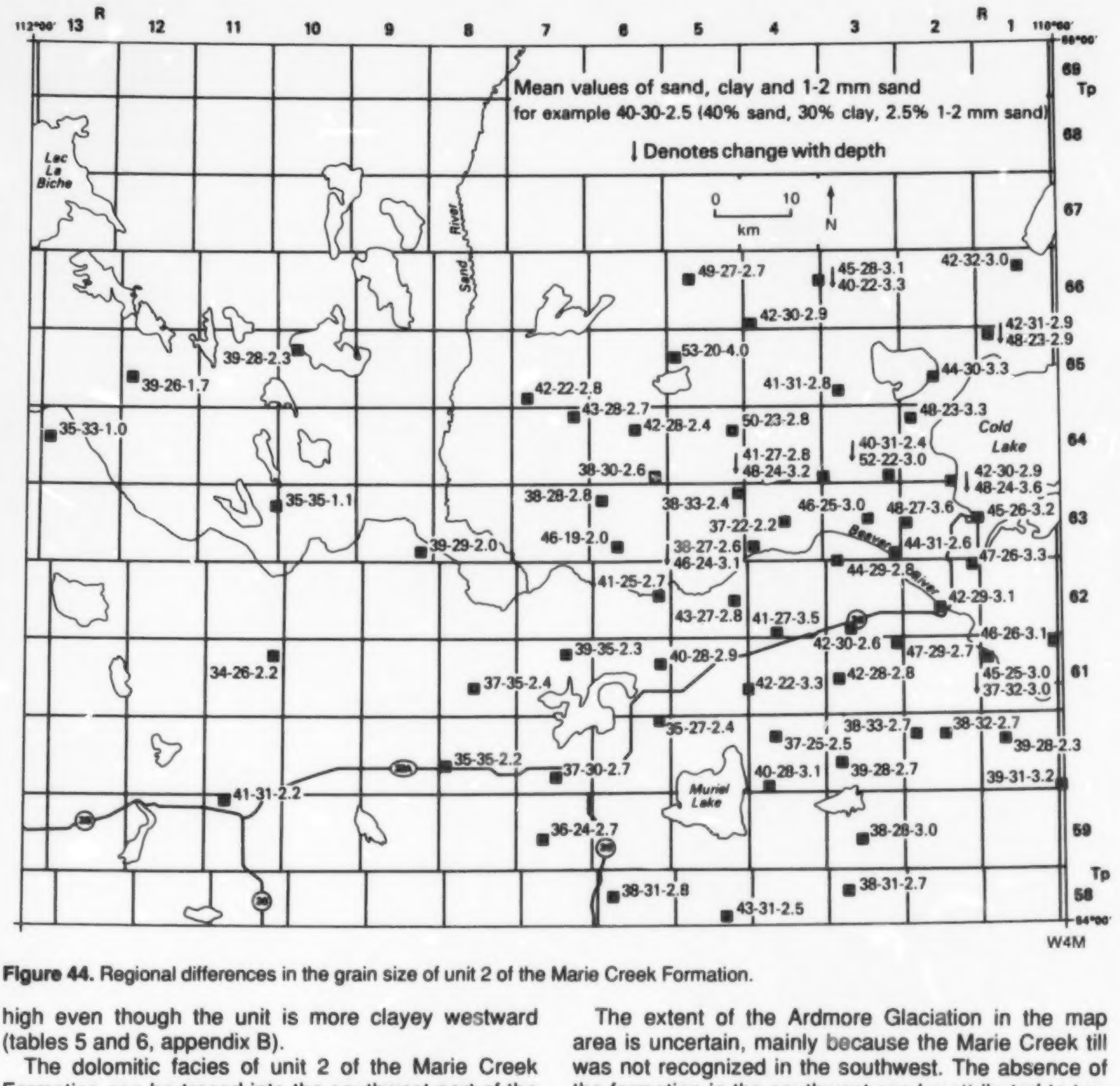


Figure 43. Difference with depth in the petrology of the very coarse sand of the Marie Creek Formation. This figure compares the normalized and non-normalized percentages of carbonate and quartz fragments and shows both an actual decrease in the amount of carbonate and an actual increase in the amount of quartz with depth in the Marie Creek Formation.

(percent quartz calculated with the exclusion of carbonates) at both the top and bottom of the unit. The results of this comparison (appendix D) show that the Marie Creek Formation contains less carbonate and has more quartz with depth. It seems probable that incorporation of the Bonnyville Formation is the source of this quartz.

Regional differences in the grain size of the smaller-than-2-mm fraction of unit 2 generally show less sand and more silt and clay toward the west (figure 44). Possibly this reflects the incorporation of underlying units that are also more clayey in the west. Except for the extreme western part of the map area, the amount of coarse sand in the Marie Creek Formation remains



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Mean values of sand, clay and 1-2 mm sand
for example 40-30-2.5 (40% sand, 30% clay, 2.5% 1-2 mm sand)
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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
49-27-2.7
45-28-3.1
40-22-3.3
42-32-3.0
42-30-2.9
42-31-2.9
48-23-2.9
39-28-2.3
53-20-4.0
39-26-1.7
44-30-3.3
42-22-2.8
41-31-2.8
43-28-2.7
48-23-3.3
35-33-1.0
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40-31-2.4
52-22-3.0
41-27-2.8
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38-28-2.8
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48-27-3.6
45-26-3.2
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37-22-2.2
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44-29-2.8
41-25-2.7
42-29-3.1
43-27-2.8
41-27-3.5
46-26-3.1
42-30-2.6
47-29-2.7
34-26-2.2
39-35-2.3
40-28-2.9
45-25-3.0
37-32-3.0
37-35-2.4
42-22-3.3
42-28-2.8
35-27-2.4
38-33-2.7
38-32-2.7
37-25-2.5
39-28-2.3
35-35-2.2
37-30-2.7
40-28-3.1
39-28-2.7
39-31-3.2
41-31-2.2
36-24-2.7
38-28-3.0
38-31-2.8
43-31-2.5
38-31-2.7

Figure 44. Regional differences in the grain size of unit 2 of the Marie Creek Formation.

high even though the unit is more clayey westward (tables 5 and 6, appendix B).

The dolomitic facies of unit 2 of the Marie Creek Formation can be traced into the southwest part of the map area, but is absent in the west and northwest. It is probable that this facies was also present in those areas but was eroded by a later glaciation and incorporated as thick, displaced masses within the overlying Grand Centre Formation (Andriashek and Fenton 1979, test hole 77SR22).

The coincidental distributions of thick deposits of the Ethel Lake and Marie Creek formations in the southwest (figures 34 and 39) indicate an ice-marginal position in this area during the Ardmore Glaciation. The thick sequences of silt, clay, sand, and gravel in the Ethel Lake Formation along this western margin are interpreted to have been deposited in a kame delta along the glacier front.

The extent of the Ardmore Glaciation in the map area is uncertain, mainly because the Marie Creek till was not recognized in the southwest. The absence of the formation in the southwest can be attributed to two reasons. First, the Ardmore Glacier may have terminated against the northeast-facing slope of the underlying rock in the southwest, only extending as a small lobe into the lowland above the buried Beverly Valley in Tp 58-59, R 9-10 (figure 38). Thick stratified sediment of the Ethel Lake Formation and till of the Marie Creek Formation were probably deposited along this terminal position (figures 34 and 40). Second, the Marie Creek till may once have occurred throughout the map area, but in the southwest it was eroded shortly after deposition. Evidence supporting this is twofold. First, the buried till in the Cooking Lake moraine, which lies west of the Sand River map area (Andriashek 1981), correlates with the Marie Creek

Formation on the basis of abundant carbonates in the very-coarse-sand fraction. If the two are the same unit, and if the Ardmore Glacier advanced due south, or slightly east of south, as indicated by the pebble fabric (figure 41), the glacier probably extended throughout the Sand River map area. Thus, the Marie Creek till was probably also deposited in the southwest but subsequently was eroded. The second line of evidence, though more speculative, is the presence of the widespread, strongly oxidized sediment in the upper part of the Bonnyville Formation in the southwest. This oxidation is much more pervasive in the west and this is used as evidence that the surface of the Bonnyville Formation was exposed to more than one weathering event in that area. The first weathering event that the Bonnyville Formation underwent followed the end of the Fort Kent Glaciation. The second weathering event followed the end of the Ardmore Glaciation, and for this to occur on the surface of the Bonnyville Formation, indicates that the Bonnyville till was not buried by the Marie Creek till. It may be coincidental, but this well-developed oxidized zone in the upper part of the Bonnyville Formation is recognized mainly in those areas where the Marie Creek till is absent. Therefore, if the Marie Creek till was deposited in the southwest, and the observations in the Cooking Lake area support this, the till must have been eroded shortly thereafter, before the weathering period that followed deglaciation.

For the most part, erosion during the nonglacial period was minor, as evidenced by the widespread preservation of the oxidized zone in the upper part of the Marie Creek Formation. Leaching of carbonates at the surface of the formation was not significant, as indicated by abundant carbonate (in both the sand and silt-clay fractions) in the upper oxidized part of the till.

Sand River Formation

Source of name: Sand River, located in the central part of the Sand River map area, NTS 73L.
Type section: Alberta Geological Survey auger test hole T9, located along the Beaver River in LSD 13, Sec 10, Tp 62, R 2, W 4 Mer in the eastern part of the Sand River map area, NTS 73L (figure 35).
Type area: The area adjacent to the Beaver River in the eastern part of the Sand River map area, NTS 73L.
Reference sections: Exposed road cut on the west side of Hwy 28 on the south side of the Beaver River crossing in LSD 14, Sec 10, Tp 62, R 2, W 4 Mer; Alberta Geological Survey auger test holes T6 (LSD 15, Sec 31, Tp 62, R 3, W 4 Mer), and T14 (LSD 4, Sec 17, Tp 60, R 3, W 4 Mer); Alberta Environment test holes E802 (LSD 5, Sec 32, Tp 61, R 5, W 4 Mer), and E804 (LSD 4, Sec 1, Tp 64, R 4, W 4 Mer).

Description of unit

The Sand River Formation consists of stratified sand and silt with lesser amounts of clay and gravel (table 2). The formation is recognized in outcrops and test holes primarily in the central and southwestern parts of the map area. Auger samples indicate that the top of the formation in the subsurface is commonly oxidized olive brown but becomes dark gray (5Y 4/1) with depth. In places the formation is oxidized both at the top and bottom, but unoxidized in between (Andriashek and Fenton 1979, test holes T18, T45, and T72).

Sand and silt of the formation are commonly oxidized olive brown (2.5Y 4/4) in outcrops. The sand is generally fine to medium-grained, well sorted, and commonly free of pebbles. The composition of the sand was not examined in detail but field observations indicate that it consists mainly of quartz with smaller amounts of igneous, metamorphic and locally derived rock. Commonly the sand is stratified, with cross-bedding visible in outcrop. Test hole observations indicate that in many places the sand is interbedded with silt. Locally, lenses of unbedded diamicton are also present.

Finer deposits, consisting of silt and interbedded silt and clay, are not common and have only a small extent. Auger samples show that whereas the clay is finely bedded with silt laminae, the silt is more massive. In places thin lenses of diamicton are interbedded with the silt and clay.

All deposits of the Sand River Formation are generally soft, moist, and easy to penetrate with an auger.

Distribution, thickness, and subcrop topography

The Sand River Formation lies mainly in the central and southwestern parts of the map area (figure 45). It is either absent or thin and discontinuous within most of the uplands. The top of the formation ranges in elevation from as high as 620 m in Tp 59, R 14 in the Vilna Plain, to as low as 530 m in Tp 62, R 1 within the Beaver Lowlands. Figures 45 and 46 show that silt and sand of the Sand River Formation form a continuous veneer (less than 5 m) over most of the Marie Creek Formation within the Beaver Lowlands. Along the southern margin of the Beaver Lowlands the formation consists mainly of silt and clay, locally mantled by sand. These deposits are as much as 18 m thick in the area west of Angling Lake, Tp 60-61, R 3-4, (figure 9, cross section E1-E1'; and figure 10, cross section N1-N1'). Thick parts of the formation also infill a depression on the surface of the Marie Creek Formation in Tp 63, R 5-7 (figures 38 and 46).

The Sand River Formation overlies the Bonnyville Formation in the southwest and northwest corners of the map area. Within the Vilna Plain, in Tp 58-59, R 12-13, the formation lies in a valley eroded into the surface of the Bonnyville Formation (figure 10, cross section E4-E4'). In the northwest, the formation consists mainly of a drape of silt and clay on a gentle slope (figures 31 and 46).

Differentiation from other units

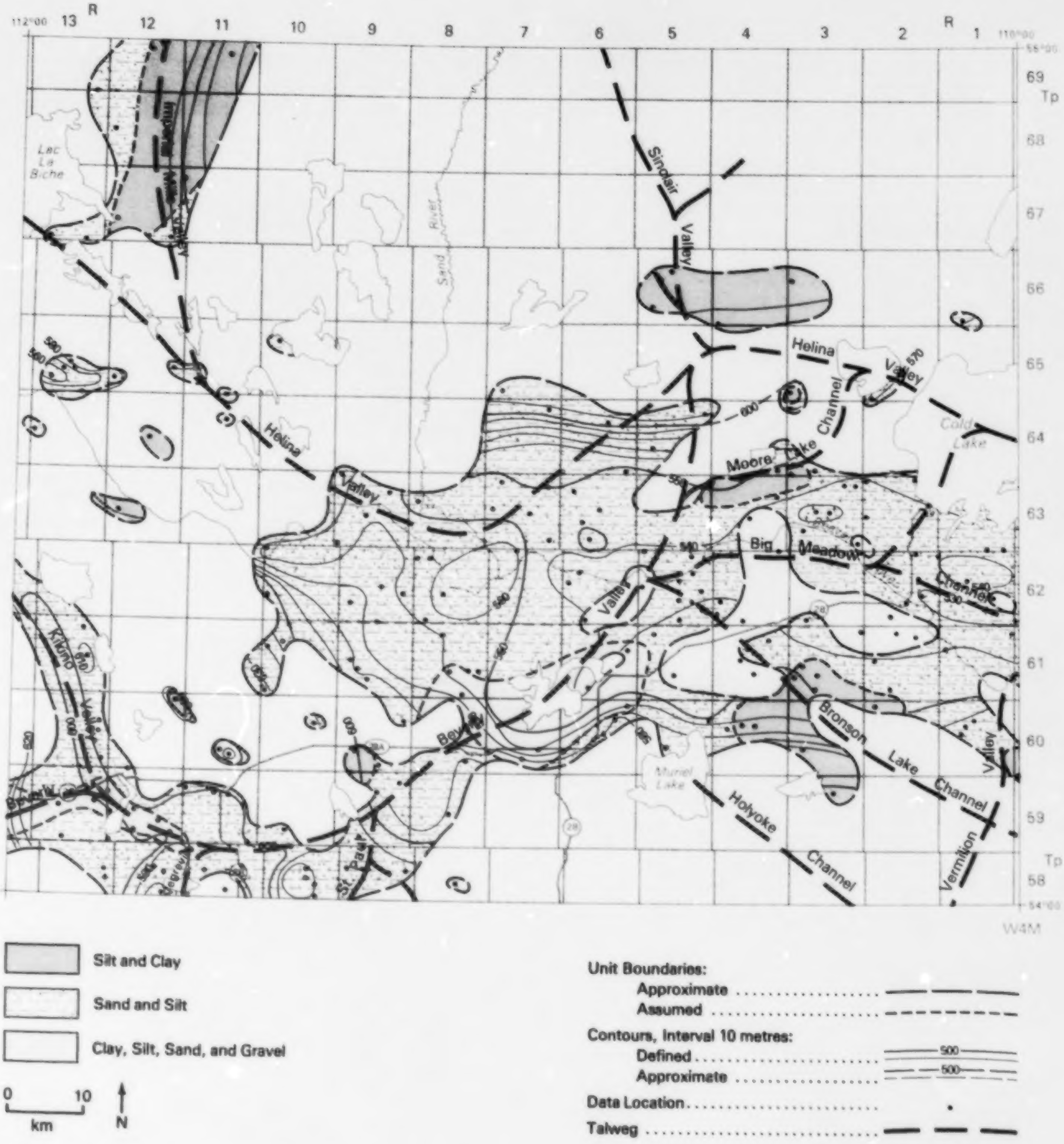
There are no distinctive lithologic or compositional properties that differentiate sediment of the Sand River Formation from stratified sediment of any of the other formations. Consequently, the Sand River Formation is differentiated and correlated mainly by stratigraphic position. As previously discussed, the Sand River Formation is differentiated from the underlying Ethel Lake Formation with certainty only in those places where the Marie Creek till separates the two.

Nature of contacts

Lower contact

In most places the Sand River Formation has a sharp contact with the underlying Marie Creek or Bonnyville tills. This contact is conformable where oxidized sediment of the Sand River Formation overlies oxidized till of the Marie Creek Formation (Andriashek and Fenton 1979, test hole T18). Conversely, the contact is disconformable in those areas where unoxidized sediment of the Sand River Formation overlies oxidized till of either the Marie Creek Formation (Andriashek and Fenton 1979, test hole T7) or the Bonnyville Formation (Andriashek and Fenton 1979, test hole 77SR15).

In a few places contacts are recognized within the Sand River Formation itself. For example, in test holes T18, T45, T72, and 77SR17 (Andriashek and Fenton 1979), the formation consists of unoxidized sand that overlies oxidized silt and clay. This indicates that possibly two or more depositional events, the first followed by a period of weathering, occurred in some places.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Sinclair Valley
Helina Valley
Helina Valley
Helina Channel
Moore Lake
Cold Lake
Big Meadow
Valley
Kikino Valley
Beverly
Beverly
Bronson Lake Channel
Holyoke Channel
Vermilion Valley
Muriel Lake
St. Paul
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Unit Boundaries:
Approximate
Assumed
Contours, Interval 10 metres:
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Approximate
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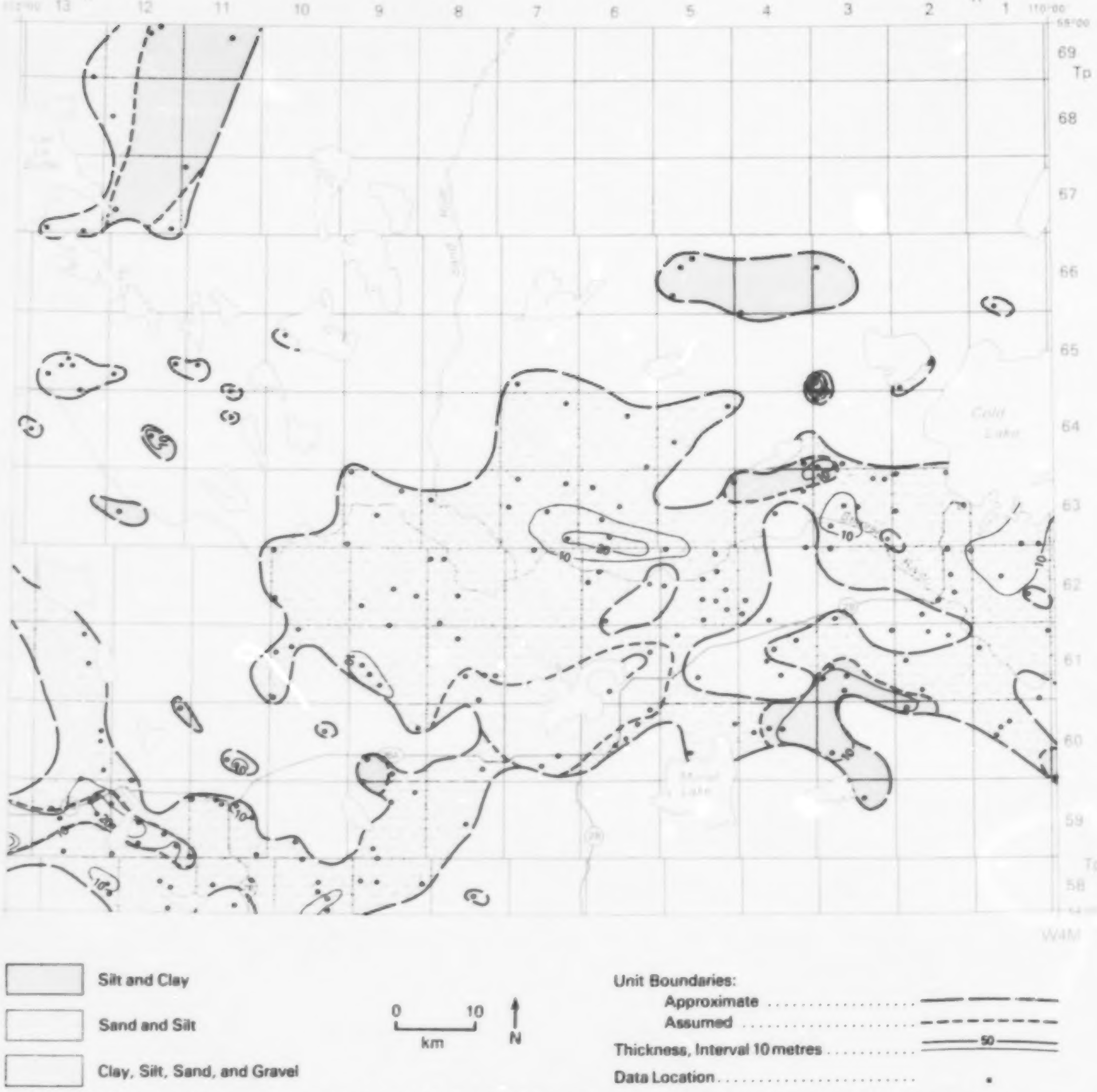
Data Location
Talweg

Figure 45. Elevation of the upper surface of the Sand River Formation. Note the extensive distribution of the formation above the buried Imperial Mills, Kikino and Beverly valleys.

Upper contact

The Sand River Formation can have either a sharp or gradational contact with the overlying Grand Centre Formation. Sharp contacts are mapped in those places where unoxidized sediment of the Grand Centre Formation overlies oxidized sand of the Sand River Formation (figure 35). Gradational contacts are indicated where the upper part of the Sand River Formation consists of sand interbedded with diamicton that is lithologically similar to the material at the base of the overlying Grand Centre Formation (Andriashek and Fenton 1979, test holes T6 and T27).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Unit Boundaries:
Approximate
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Thickness, Interval 10 metres
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Data Location

Figure 46. Thickness of clay, silt, sand, and gravel in the Sand River Formation. Note the widespread, thin deposits in the central part of the map area.

Origin of sediment in the Sand River Formation

The origin of the stratified sediment of the Sand River Formation is uncertain. Not all of the formation is considered to have the same origin, nor was it all deposited at the same time. Some of the stratified deposits, particularly the silt and clay, were probably deposited during the later phases of the Ardmore Glaciation. It is uncertain whether the fine sediment had a glaciolacustrine or a glaciofluvial origin. A large glacial lake above the buried Imperial Mills Valley is indicated by the widespread deposits of silt and clay in that area. Evidence that fine-grained sediments were deposited during the later phases of the Ardmore Glaciation and not during the early phases of the following Cold Lake Glaciation, is an oxidized zone that locally penetrates through the stratified sediment and into the till of the underlying Marie Creek Formation (Andriashek and Fenton 1979, test holes T23 and

77SR23). This indicates that the stratified sediment was deposited immediately after the Marie Creek till and that both were subject to the same weathering event following the Ardmore Glaciation. In test hole T9 (figure 35) this stratified sediment apparently was thick enough to prevent the oxidation from reaching the till of the Marie Creek Formation.

The coarser-grained silt and sand that are widespread in the central part of the map area are either glaciofluvial or glaciolacustrine sediment. The abundance of fine-grained sand and silt, locally interbedded with thin diamicton layers, indicates deposition in a glacial lake. The presence of gravel beds in some areas indicates a glaciofluvial origin, though these could also be interpreted as beach sediment.

Most of the sand and gravel in the Sand River Formation was deposited during the early phases of the last glaciation in the map area, here named the Cold Lake Glaciation. Evidence for this consists of widespread unoxidized sand that overlies both oxidized silt and clay of the Sand River Formation (Andriashek and Fenton 1979, test hole 77SR17) and oxidized till of the Marie Creek and Bonnyville Formations (Andriashek and Fenton 1979, test holes T6, T7, 77SR15, 77SR27, 77SR28, and 77SR29). This stratigraphic sequence indicates that the sand was not exposed or weathered for very long prior to burial by till during the Cold Lake Glaciation.

Grand Centre Formation

Source of name: Town of Grand Centre, Alberta, located in Tp 63, R 2, W 4 Mer in the eastern part of the Sand River map area, NTS 73L.

Type section: The Grand Centre Formation consists of four members, each of which has a designated type section. These members are as follows:

Hilda Lake Member. Type section: Section LA81-1, exposed road cut along the west bank of the Marie Creek in LSD 1, Sec 30, Tp 63, R 2, W 4 Mer, in the Sand River map area, NTS 73L. At this location the Hilda Lake Member overlies the Marie Creek Formation and is overlain by the Reita Lake Member of the Grand Centre Formation.

Reita Lake Member. Type section: Section LA81-1, exposed road cut along the west bank of the Marie Creek in LSD 1, Sec 30, Tp 63, R 2, W 4 Mer, in the Sand River map area, NTS 73L. At this location the Reita Lake Member overlies the Hilda Lake Member of the Grand Centre Formation and is exposed at the surface.

Kehiwin Lake Member. Type section: Alberta Geological Survey auger test hole 77SR17, located in LSD 15, Sec 9, Tp 61, R 8, W 4 Mer, in the Sand River map area, NTS 73L. At this location the Kehiwin Lake Member overlies the Reita Lake Member of the Grand Centre Formation and is exposed at the surface.

Vilna Member. Type section: Alberta Geological Survey auger test hole 77SR7, located in LSD 16, Sec 29, Tp 59, R 11, W 4 Mer, in the Sand River map area, NTS 73L. At this location the Vilna Member overlies the Kehiwin Lake Member of the Grand Centre Formation and is exposed at the surface.

Type area: There is no type area defined for the Grand Centre Formation as such. Rather, type areas have been defined for each of the members. The type area for both the Hilda Lake and Reita Lake members is in the eastern part of the map area, north and west of the town of Grand Centre. The type area for the Kehiwin Lake Member is in the central part of the map area near the town of Glendon. The type area for the Vilna Member is near the town of Ashmont in the southwest corner of the map area.

Reference sections: The reference sections are given in the descriptions of each member.

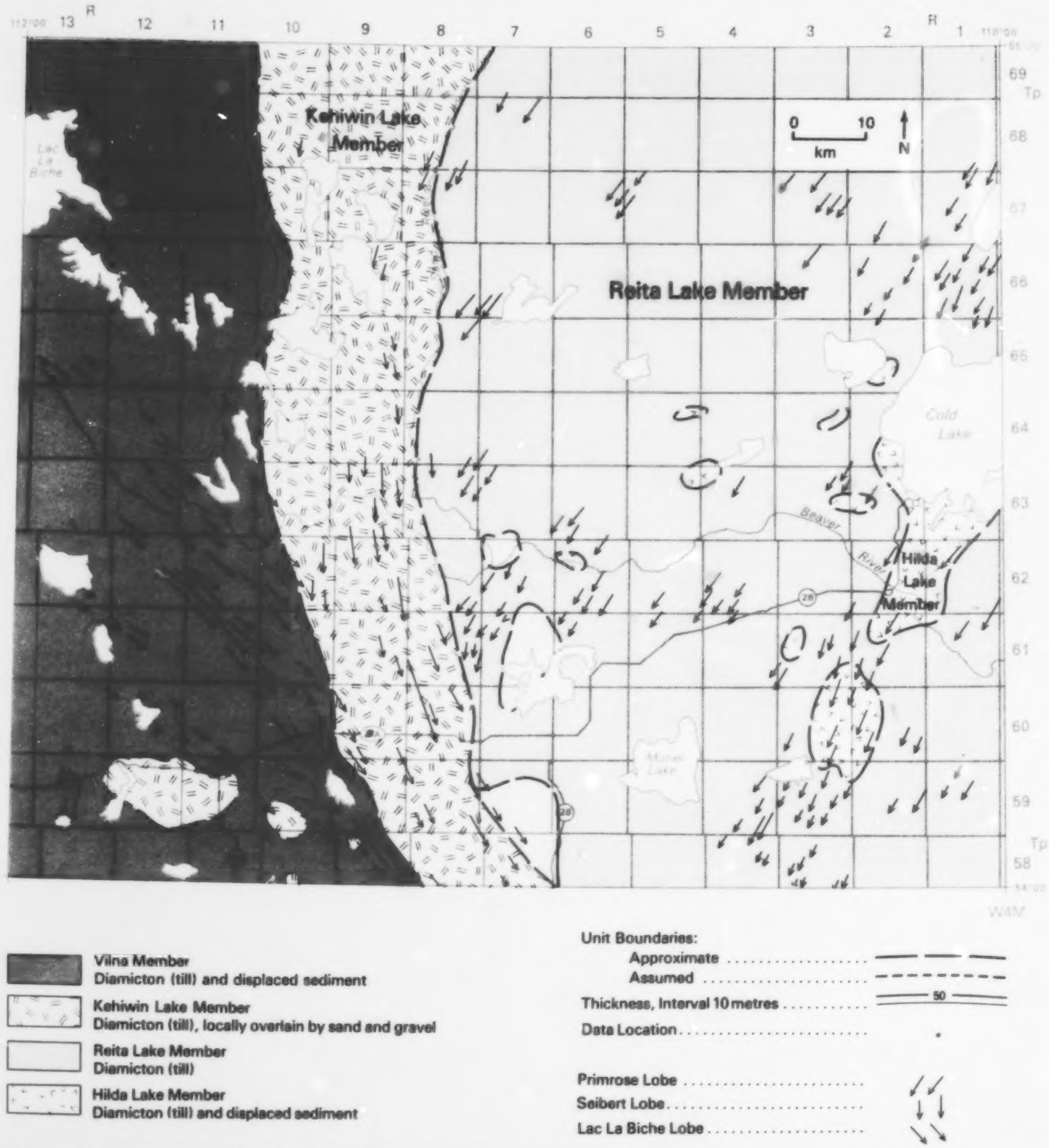
General description of the formation

The Grand Centre Formation is the uppermost formation in the Quaternary sequence in the Sand River map area (table 2). It is widespread and lies at the surface in most places, except where it is buried by postglacial stratified sediment (figure 47; and Fenton and Andriashek 1983, in pocket). The formation is composed mainly of diamicton that is generally characterized by a sandy-clay texture, an abundance of igneous and metamorphic rock in the very coarse sand, a soft consistence, and a dark gray brown color.

The top of the formation ranges in elevation from as high as 790 m in the Heart and Muriel highlands, to less than 550 m in the Beaver Lowlands (figure 48). It is one of the thickest stratigraphic units in the map area, ranging between 10 and 30 m over most of its extent (figure 49). Large areas of very thick (60 m) sediment of the formation are mapped within the Kehiwin Plateau and Vilna Plain and within the Cache Upland. Small areas of exceptionally thick sediment are mapped within the isolated highlands that lie south of the larger lakes in the map area (Cold Lake, Marie Lake, Primrose Lake, Wolf Lake, Muriel Lake). In most of these highlands the Grand Centre Formation consists of ice-thrust, glacially displaced masses of older sediment, including diamicton that is not characteristic of the Grand Centre Formation. In the Wolf and Primrose highlands for example, the Grand Centre Formation consists of more than 60 m of ice-thrust Marie Creek till (Andriashek and Fenton 1979, test holes T1 and 77SR33).

The Grand Centre Formation is differentiated from other units on the basis of stratigraphic position, color, structure, grain size, composition of the very coarse sand, and electric logs. The formation contains the uppermost diamicton and overlies either stratified sediment of the Sand River Formation or diamicton of the Marie Creek and Bonnyville formations (figure 10, cross section N1-N1'). The formation is generally darker than the oxidized upper parts of the Marie Creek and Bonnyville formations. All members of the Grand Centre Formation contain more igneous and metamorphic rock in the very-coarse-sand fraction than either of the Marie Creek or Bonnyville formations. The members contain much less quartz than the Bonnyville Formation, and significantly less carbonate than the upper part of unit 2 of the Marie Creek Formation (figure 18). One exception is the Kehiwin Lake Member; it has as much quartz as the Bonnyville Formation (figure 18). The Grand Centre Formation has less electrical resistance than the top of the Marie Creek Formation. In the eastern half of the map area the resistance of the Grand Centre Formation is less than that of the Bonnyville Formation, but the reverse is true in the west where, in places, the Bonnyville Formation is more clayey. The Grand Centre Formation may be difficult to differentiate from the lower till units in those areas where significant amounts of glacially displaced blocks of older sediment, especially till, are incorporated into the formation. This occurs within many of the highland areas.

On the basis of differences in grain size, color, orientation of glacial ice-flow indicators, and strati-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Kehiwin Lake Member
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Vilna Member
Diamicton (till) and displaced sediment
Kehiwin Lake Member
Diamicton (till), locally overlain by sand and gravel
Reita Lake Member
Diamicton (till)
Hilda Lake Member
Diamicton (till) and displaced sediment
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
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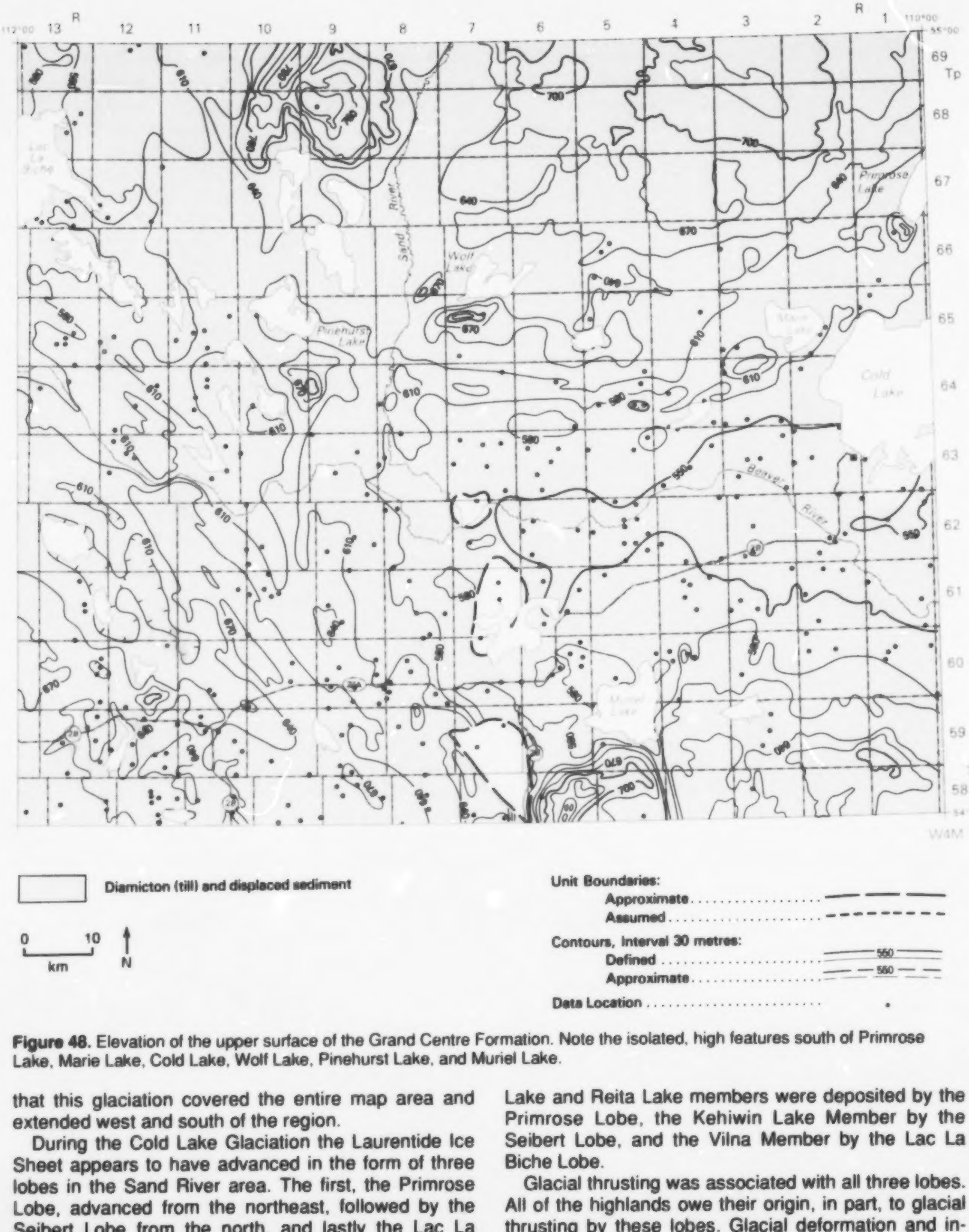
Data Location
Primrose Lobe
Seibert Lobe
Lac La Biche Lobe

Figure 47. Outcrop map of the Hilda Lake, Reita Lake, Kehiwin Lake, and Vilna members of the Grand Centre Formation. The figure also shows the glacial flow directions of the Primrose Lobe, Seibert Lobe and Lac La Biche Lobe during the Cold Lake Glaciation.

graphic position, the Grand Centre Formation is divided into four members (figure 47). From oldest to youngest, these are the Hilda Lake Member, the Reita Lake Member, the Kehiwin Lake Member, and the Vilna Member (table 2). Detailed descriptions of these members are given in the following sections.

Origin of the sediment in the Grand Centre Formation

The Grand Centre Formation consists mainly of till that was deposited during the last major glaciation in the map area, the Cold Lake Glaciation. The distribution and extent of the Grand Centre Formation indicates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Sand River
Wolf Lake
Pinehurst Lake
Primrose Lake
Marie Lake
Cold Lake
Beaver River
Muriel Lake
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Contours, Interval 30 metres:
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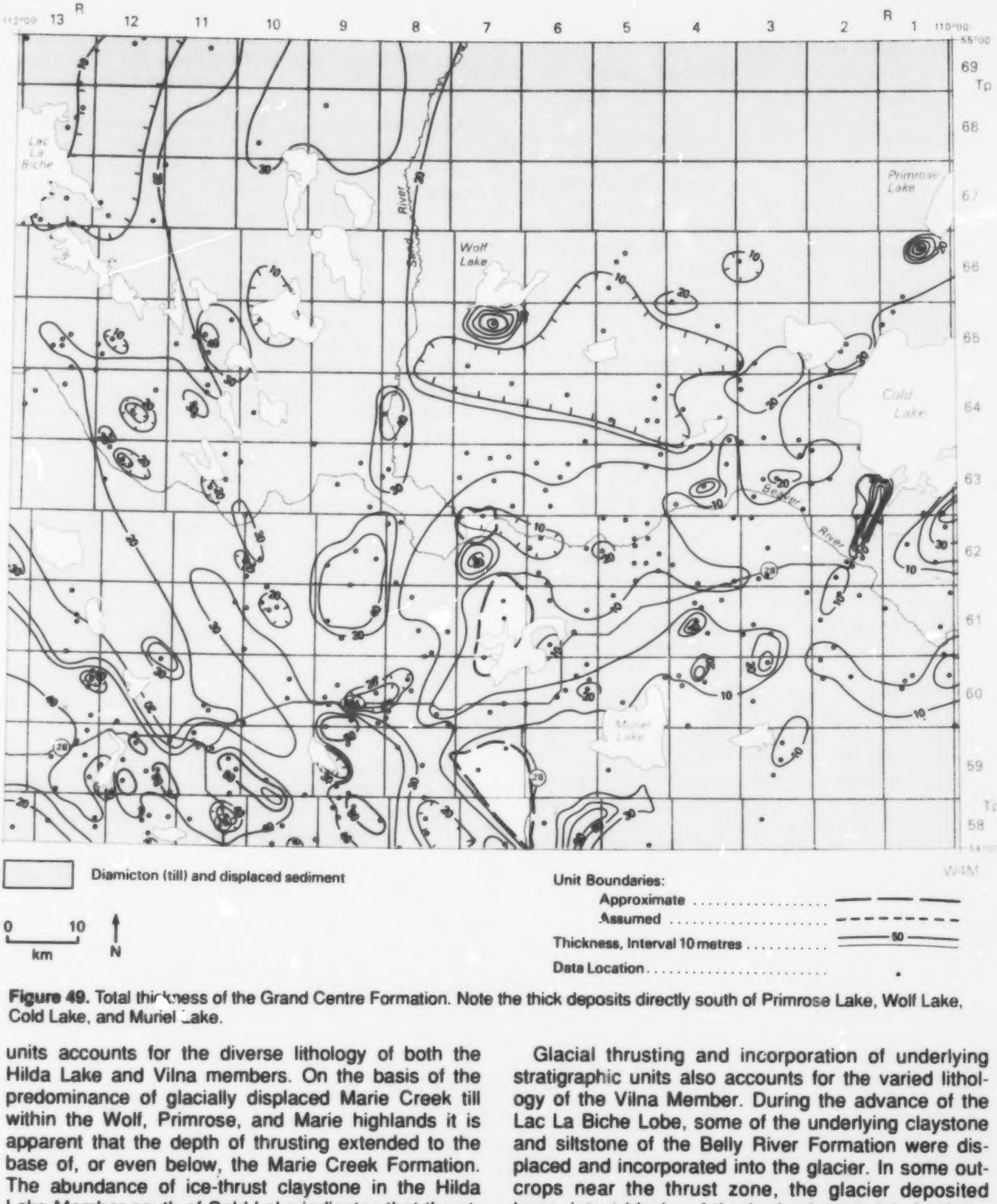
Data Location

Figure 48. Elevation of the upper surface of the Grand Centre Formation. Note the isolated, high features south of Primrose Lake, Marie Lake, Cold Lake, Wolf Lake, Pinehurst Lake, and Muriel Lake.

that this glaciation covered the entire map area and extended west and south of the region.

During the Cold Lake Glaciation the Laurentide Ice Sheet appears to have advanced in the form of three lobes in the Sand River area. The first, the Primrose Lobe, advanced from the northeast, followed by the Seibert Lobe from the north, and lastly the Lac La Biche Lobe from the northwest (figure 47). The Hilda Lake and Reita Lake members were deposited by the Primrose Lobe, the Kehiwin Lake Member by the Seibert Lobe, and the Vilna Member by the Lac La Biche Lobe.

Glacial thrusting was associated with all three lobes. All of the highlands owe their origin, in part, to glacial thrusting by these lobes. Glacial deformation and incorporation of large masses of underlying stratigraphic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Primrose Lake
Wolf Lake
Cold Lake
Muriel Lake
Sand River
Beaver River
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Diamicton (till) and displaced sediment
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Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
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Data Location

Figure 49. Total thickness of the Grand Centre Formation. Note the thick deposits directly south of Primrose Lake, Wolf Lake, Cold Lake, and Muriel Lake.

units accounts for the diverse lithology of both the Hilda Lake and Vilna members. On the basis of the predominance of glacially displaced Marie Creek till within the Wolf, Primrose, and Marie highlands it is apparent that the depth of thrusting extended to the base of, or even below, the Marie Creek Formation. The abundance of ice-thrust claystone in the Hilda Lake Member south of Cold Lake indicates that thrusting extended at least as deep as the Lea Park Formation, which probably occurs along the south flank of the buried Helina Valley.

Glacial thrusting and incorporation of underlying stratigraphic units also accounts for the varied lithology of the Vilna Member. During the advance of the Lac La Biche Lobe, some of the underlying claystone and siltstone of the Belly River Formation were displaced and incorporated into the glacier. In some outcrops near the thrust zone, the glacier deposited large, intact blocks of the bedrock material. As these blocks were transported farther down-ice from the source areas, they were glacially comminuted and deposited as diamicton composed almost entirely of rounded pebbles of reworked claystone.

Hilda Lake Member

Source of name: Hilda Lake, Alberta, located in Tp 64, R 3, W 4 Mer in the eastern part of the Sand River map area, NTS 73L.

Type section: Section LA81-1, exposed road cut along the western bank of the Marie Creek in LSD 1, Sec 30, Tp 63, R 2, W 4 Mer in the Sand River map area, NTS 73L (figure 50). At this location the Hilda Lake Member overlies the Marie Creek Formation and is overlain by the Reita Lake Member of the Grand Centre Formation.

Type area: The area north of the Beaver River outlined by Tp 62-65, R 1-6 in the eastern part of the Sand River map area, NTS 73L.

Reference sections: Exposed road cuts on the southern side of LSD 16, Sec 13, Tp 62, R 2, W 4 Mer, and along Highway 28 in LSD 13, Sec 10, Tp 62, R 2, W 4 Mer; Alberta Geological Survey auger test holes T2 (LSD 4, Sec 15, Tp 65, R 2, W 4 Mer), T7 (LSD 4, Sec 1, Tp 64, R 6, W 4 Mer), and T32 (LSD 12, Sec 1, Tp 64, R 3, W 4 Mer).

Description of unit

The Hilda Lake Member has been mapped from both outcrop and test hole samples. The member consists of clayey diamicton that locally contains blocks of stratigraphically older diamicton, stratified sediment, and claystone. The member is very dark gray brown (2.5Y 3/2) at the top, but becomes very dark gray (5Y 3/1) with depth. In outcrop the diamicton is generally unjointed to slightly fissile though locally larger, slightly iron-oxide stained fractures are present. The material is moderately stiff but tends to cling to a pick or shovel when excavated. Directly south of Cold Lake large amounts of glacially transported blocks of claystone, sand, and silt and older diamicton form much of the member (plate 5). These were deposited within a southwest-oriented glacially streamlined ridge (Fenton and Andriashek 1983, in pocket).

The grain size of the smaller-than-2-mm fraction of the diamicton is about 27% sand, 30% silt, and 43% clay, with less than 1% very coarse sand (figure 18). The range in grain size is shown in table 7, appendix B. The diamicton characteristically contains few pebbles or granules. The clayey texture results in a moisture content of about 13% and makes the member soft and easy to penetrate with an auger.

The composition of the very coarse sand is about 69% igneous and metamorphic rock, 23% quartz, 2% limestone, 3% dolostone, 1 to 2% local rock, and 1% quartzite and quartz sandstone (figure 18). The range in composition is shown in table 7, appendix B.

Calcareous material makes up about 11% of the silt-clay fraction (calcite/dolomite ratio = 0.24, figure 18).

The clay minerals of a few representative samples consist of about 50% illite, 20% kaolinite, 25% smectite, and 5% chlorite (appendix C).

The Hilda Lake Member has lower electrical resistance than the underlying Sand River and Marie Creek Formations and the overlying Reita Lake Member.

Distribution, thickness, and subcrop topography

The Hilda Lake Member is confined mainly to the central and eastern part of the Sand River map area (figure 51). It extends as far north as Tp 66, R 5 within the Marguerite Upland, and as far south as the base of the Reita and Moose Lake uplands. The top of the member ranges in elevation from as high as 630 m in the north to as low as 530 m within the Beaver Lowlands. The member is noticeably absent along a trend that roughly parallels the Beaver River in the eastern part of the map area (figure 51).

Although in most places the Hilda Lake Member is overlain by the Reita Lake Member (figure 9, cross section E2-E2'), it outcrops within a high hummocky ridge south of Cold Lake in Tp 61-63, R 1-2, and within glacially streamlined ridges near Angling Lake in Tp 60, R 2-3 (Fenton and Andriashek 1983, in pocket). Glacially displaced and transported blocks of claystone, silt, and sand are exposed in both areas (plate 5).

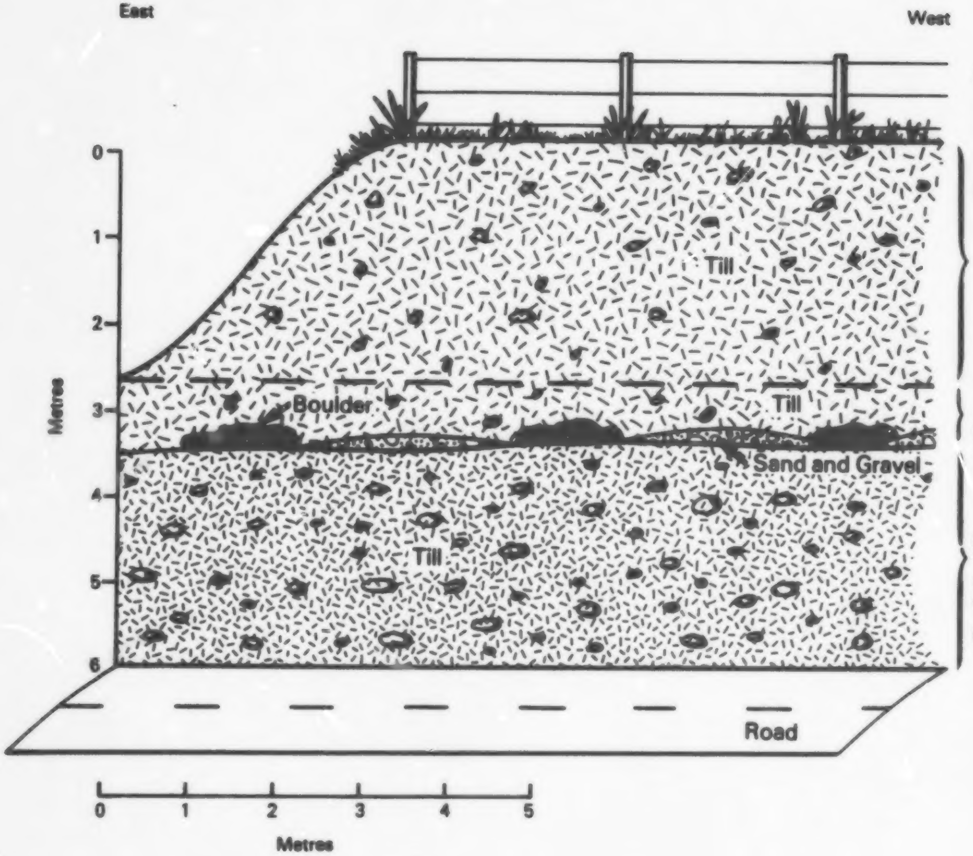
The thickest parts of the member are found within the hummocky ridge directly south of Cold Lake, where as much as 53 m are mapped (figure 52). Thick sediment is also found within a number of discontinuous ridges located along the base of the Medley and Marguerite uplands and west of Cold Lake in Tp 65, R 2. Elsewhere, the Hilda Lake Member is generally less than 10 m thick.

Differentiation from other units

The Hilda Lake Member is the lowest member of the Grand Centre Formation and for the most part it is overlain by the Reita Lake Member (figure 9, cross sections E1-E1' and E2-E2'). The two are differentiated by differences in grain size and color: the Hilda Lake Member is much more clayey and in outcrop generally is darker gray brown compared to the gray brown to olive brown color of the Reita Lake Member. Both members have glacially streamlined landforms oriented in a southwest direction (figure 47).

The Hilda Lake Member underlies the Kehiwin Lake Member in the central part of the map area (figure 9, cross section E3-E3'). It is more clayey, darker gray brown and contains more igneous and metamorphic rock in the very coarse sand than the Kehiwin Lake Member (figure 18). As well, glacially streamlined features on the surface of the Hilda Lake Member are oriented in a southwestern direction, whereas those on the surface of the Kehiwin Lake Member are oriented in a southern direction (figure 47).

The Hilda Lake Member is separated from the Vilna Member, both geographically and stratigraphically, by the Reita Lake and Kehiwin Lake members (figure 10, cross section N2-N2'; and figure 47). Both members



Grand Centre Formation

Reita Lake Member: Dark gray brown (2.5Y 4/2) sandy clay diamicton; fissile to massive; soft; slight iron staining along joints; few pebbles; increase in clay content with depth.

Depth (m)	Grain size %Sand	Grain size %Clay	Sand %1-2 mm	Matrix Vol. CO_2	Carbonate $\%CO_3$	$\frac{\text{Calcite}}{\text{Dolomite}}$
1	37	24	1.7	22	9	0.33
2	33	35	1.6	32	13	0.27
3	33	52	1.4	29	12	0.40

Hilda Lake Member: Very dark gray brown (2.5Y 3/2) clayey diamicton; stiff; few pebbles; boulder concentration and discontinuous sand and gravel lenses at base of unit.

Depth (m)	Grain size %Sand	Grain size %Clay	Sand %1-2 mm	Matrix Vol. CO_2	Carbonate $\%CO_3$	$\frac{\text{Calcite}}{\text{Dolomite}}$
3.5	20	46	0.7	23	10	0.12

Marie Creek Formation

Olive brown (2.5Y 4/4) sandy diamicton; dense, highly fractured; with iron and manganese staining; very stony and pebbly.

Depth (m)	Grain size %Sand	Grain size %Clay	Sand %1-2 mm	Matrix Vol. CO_2	Carbonate $\%CO_3$	$\frac{\text{Calcite}}{\text{Dolomite}}$
4	55	26	3.1	38	16	0.20
5	52	13	4.2	30	13	0.22
6	55	10	3.1	31	13	0.19

Figure 50. Type section of the Hilda Lake Member and Reita Lake Member of the Grand Centre Formation. Section LA81-1 located along the western bank of the Marie Creek (LSD 1, Sec 30, Tp 63, R 2, W 4 Mer). View looking south.

Plate 5a. Glacially displaced shale within the Hilda Lake Member of the Grand Centre Formation. Note overturned bed of light colored bentonite. Section SRA-47 (LSD 15, Sec 36, Tp 62, R 2, W 4 Mer).

Plate 5b. Glacially displaced shale and ironstone within the Hilda Lake Member of the Grand Centre Formation. Section SRA-260 (LSD 5, Sec 26, Tp 60, R 3, W 4 Mer).

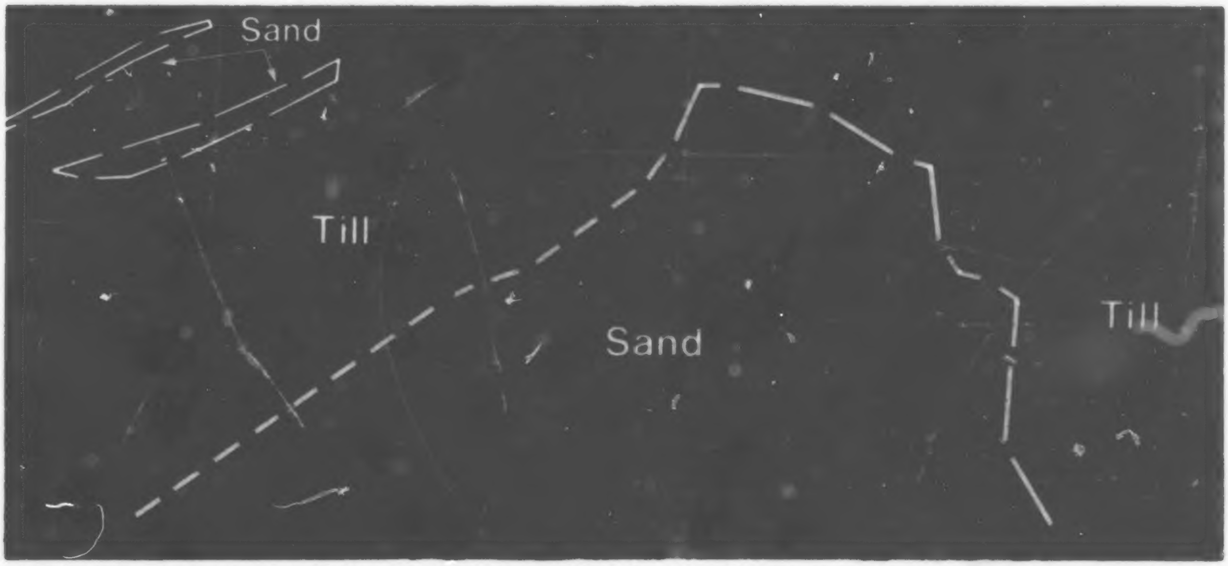
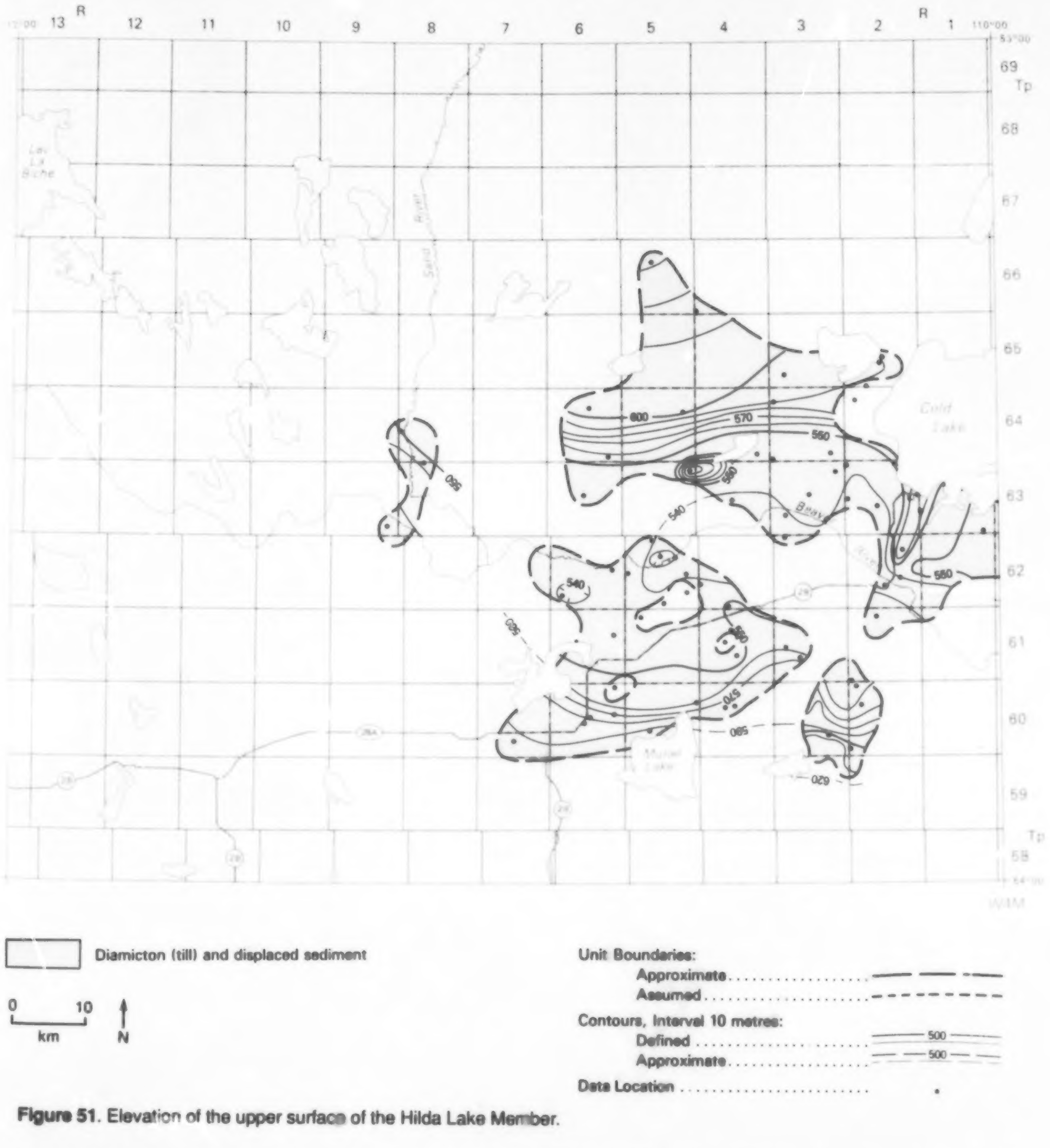


Plate 5c. Glacially displaced stratified sediment within the Hilda Lake Member of the Grand Centre Formation. Note steeply folded beds of sand (LSD 13, Sec 21, Tp 60, R 2, W 4 Mer).

are clayey and dark gray, but glacially streamlined landforms on the surface of the Vilna Member are oriented in a southeastern direction whereas those on the surface of the Hilda Lake Member are oriented to the southwest (figure 47).

The Hilda Lake Member is differentiated from the Marie Creek Formation by its more abundant clay and less abundant sand content (particularly very coarse sand), its more abundant igneous and metamorphic rock content in the very coarse sand (figure 18) and its less abundant carbonate content in the silt-clay fraction. In outcrop the Hilda Lake Member is very dark gray brown and is unfractured to slightly fissile; this contrasts markedly with the highly fractured, olive-brown color of the Marie Creek Formation (plate 4).

The Hilda Lake Member directly overlies the Bonnyville Formation in only a few places. The member has more igneous and metamorphic rock and less quartz in the very coarse sand (figure 18). The Hilda Lake Member contains the most clayey diamicton in the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Lac La Biche
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Cold Lake
Beaver River
Muriel Lake
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Unit Boundaries:
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Assumed
Contours, Interval 10 metres:
Defined
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Approximate
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Data Location

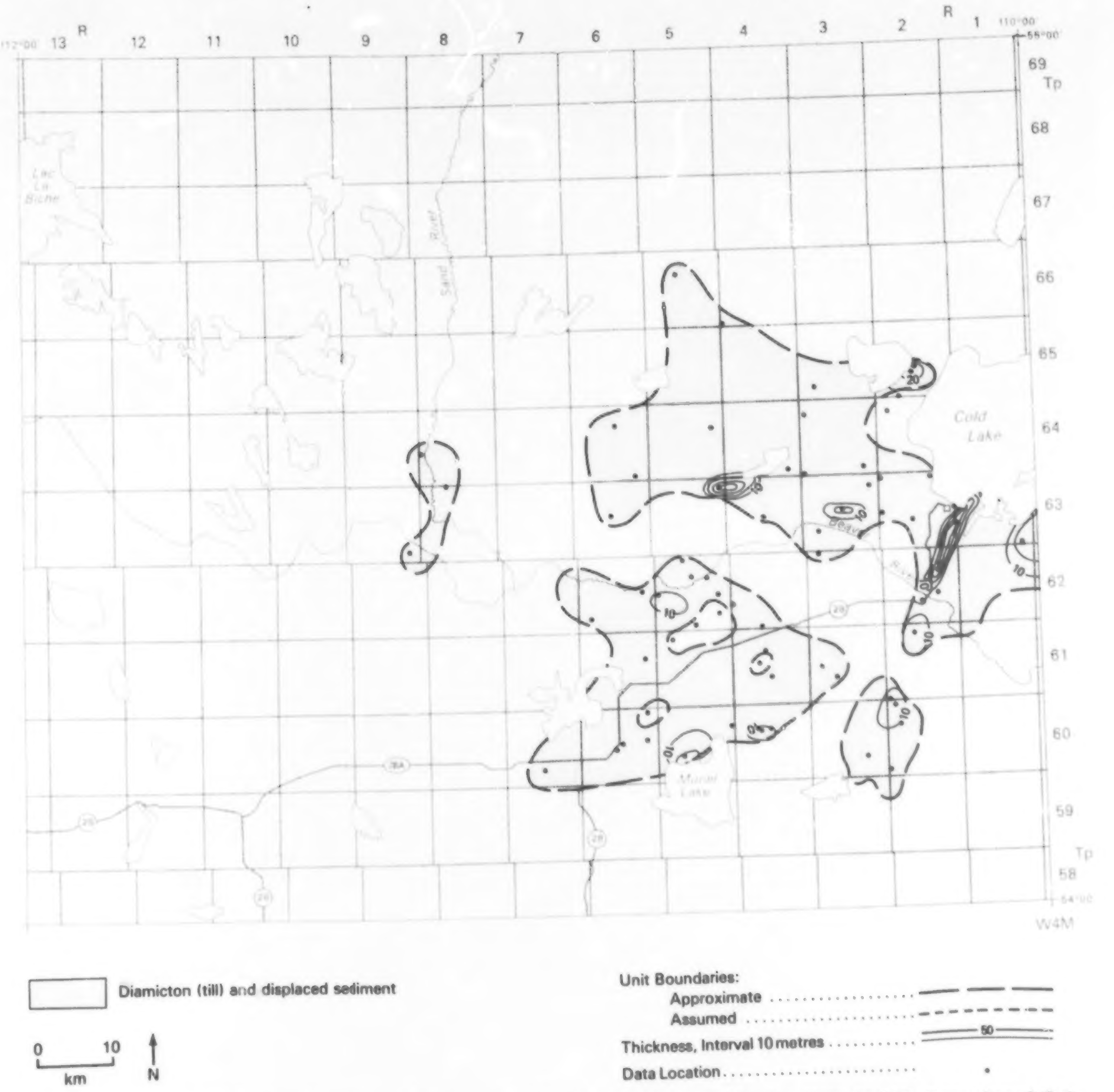
Figure 51. Elevation of the upper surface of the Hilda Lake Member.

east whereas the Bonnyville Formation contains the most sandy diamicton.

Nature of contacts

Lower contact

The Hilda Lake Member rests mainly on the Sand River or Marie Creek formations. The contact with the Sand River Formation is generally sharp, with gradational contacts indicated in only a few places (Andriashek and Fenton 1979, test holes T6 and T18). The contact can be difficult to establish in some places because: (1) the Hilda Lake Member contains bodies of glacially displaced stratified sediment, similar to that of the Sand River Formation; and (2) the Sand River Formation in places contains beds of diamicton with properties similar to those of the Hilda Lake Member.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Sand River
Cold Lake
Beaver River
Muriel Lake
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Diamicton (till) and displaced sediment
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km
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Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 52. Thickness of diamicton and glacially displaced sediment in the Hilda Lake Member. Note the thick, linear deposit that extends southwest of Cold Lake.

The contact between the Hilda Lake Member and the Marie Creek Formation is generally sharp and well defined. In places a boulder concentration lies at the contact (plate 3). The Hilda Lake Member typically has a much lower resistance than the top of the Marie Creek Formation (figure 12). Directly south of Cold Lake the contact may be difficult to establish because the top of the Marie Creek Formation has been glacially thrust and incorporated into the Hilda Lake Member.

Upper contact

On the basis of grain size, the Hilda Lake Member is gradational with the base of the Reita Lake Member (Andriashek and Fenton 1979, test holes T7, T25, T32, and 77SR18). In Tp 63-64, R 3-5, stratified sediment locally lies at the contact between the two members (Andriashek and Fenton 1979, test holes T6, T12, and T27). It is not known if this stratified sediment was deposited contemporaneously with diamicton of the two members, perhaps as basal melt-out sand lenses, or if its presence indicates a break in the glacial depositional sequence.

Origin and differences in the properties of the sediment in the Hilda Lake Member

Diamicton within the Hilda Lake Member is till deposited by the Primrose Lobe during the early phases of the Cold Lake Glaciation. Glacial thrusting associated with this advance eroded the basins of the major lakes in the east, including Primrose, Marie, Cold, Wolf, and Muriel lakes. Most of the differences in the properties of the Hilda Lake Member probably relate to different amounts of glacially displaced older sediment within the member. The clay in the Hilda Lake till is probably due to incorporation and reworking of claystone that was thrust from the southern flank of the buried Helina Valley. Evidence for this consists of large blocks of claystone that lie at the surface south of Cold Lake and near Angling Lake (Fenton and Andriashek 1983, in pocket; and plate 5). It is similarly thought that claystone was thrust from beneath Muriel Lake and Moose Lake at this time.

Reita Lake Member

Source of name: Reita Lake, Alberta, located in Tp 59, R 3, W 4 Mer in the southeastern part of the Sand River map area, NTS 73L.

Type section: Section LA81-1, exposed road cut along the western bank of the Marie Creek in LSD 1, Sec 30, Tp 63, R 2, W 4 Mer, in the eastern part of the Sand River map area, NTS 73L (figure 50). At this location the Reita Lake Member is exposed at the surface and overlies the Hilda Lake Member of the Grand Centre Formation.

Type area: The area within the Beaver Lowlands, Tp 60-64, R 1-6, W 4 Mer, in the eastern part of the Sand River map area, NTS 73L.

Reference sections: Exposed road cuts along the banks of the Redspring Creek in LSD 11, Sec 28, Tp 60, R 1, W 4 Mer; Alberta Geological Survey auger test holes T12 (LSD 4, Sec 4, Tp 62, R 4, W 4 Mer), T25 (LSD 4, Sec 24, Tp 62, R 6, W 4 Mer), T27 (LSD 4, Sec 6, Tp 64, R 3, W 4 Mer), and T32 (LSD 12, Sec 1, Tp 64, R 3, W 4 Mer).

Description of unit

The Reita Lake Member consists mainly of clayey-sand diamicton that outcrops over most of the eastern half of the Sand River map area. Locally, the member is composed of diamicton interbedded with either stratified sediment or glacially incorporated beds of older diamicton. The member has been mapped from both outcrops and test hole samples.

The Reita Lake Member is oxidized dark gray brown (2.5Y 4/2) at the top, but becomes unoxidized dark gray (5Y 3/1) with depth. In outcrop the upper part of the member is soft and slightly fissile, but becomes more compact and massive with depth (plate 4). Locally, lenses of sand and silt are interbedded with the diamicton, but the extent and distribution of these are unknown. The member is moist and relatively easy to penetrate with an auger.

The grain size of the smaller-than-2-mm fraction of the diamicton is about 38% sand, 26% silt, and 36% clay, with about 1.5 to 2% very coarse sand (figure 18). The range in grain size is shown in table 8, appendix B. The diamicton typically contains few pebbles or granules.

The moisture content of the Reita Lake Member differs from place to place, probably because the member is exposed in most places and is subject to different amounts of precipitation. The moisture content from auger samples ranges from about 10% in the sandy samples to as much as 16% in the clayey samples (table 8, appendix B).

The composition of the very coarse sand is about 69% igneous and metamorphic rock, 25% quartz, 2% limestone, 3% dolostone, 1% quartzite and quartz sandstone and less than 1% local rock (figure 18). The range in composition is shown in table 8 (appendix B).

Calcareous material makes up about 11% of the silt-clay fraction (calcite/dolomite ratio = 0.28, figure 18).

The clay minerals of a few representative samples consists of about 55% illite, 25% kaolinite, 15% smectite, and 5% chlorite (appendix C).

Glacially streamlined features on the surface of the Reita Lake Member characteristically have a southwestern direction (figure 47). Orientations of pebbles in the diamicton, measured within one of these streamlined features, are less consistent; they show a weak bimodal distribution with some elements parallel to the streamlined features and others perpendicular to that orientation (figure 53).

Distribution, thickness, and topography

The Reita Lake Member is the surface unit over most of the eastern half of the map area and probably extends south into the Vermilion map area (figure 54). The western limit of the member is near the Sand River in the north-central part of the map area and near the Kehiwin Creek and Kehiwin Lake in the south-central part. The top of the member ranges in elevation from as high as 790 m within the Muriel Highland in the south to as low as 550 m in the eastern part of the Beaver Lowlands (figure 54).

The member is generally less than 10 m thick over most of the Reita and Marguerite uplands and within segments of the Beaver Lowlands (figure 9, cross section E1-E1'; and figure 55). Smaller areas of thicker sediment (30 m) are scattered along the western margin of the member and along the northern and southern flanks of the Beaver Lowlands. The thickest sediments are found within the isolated highlands in the

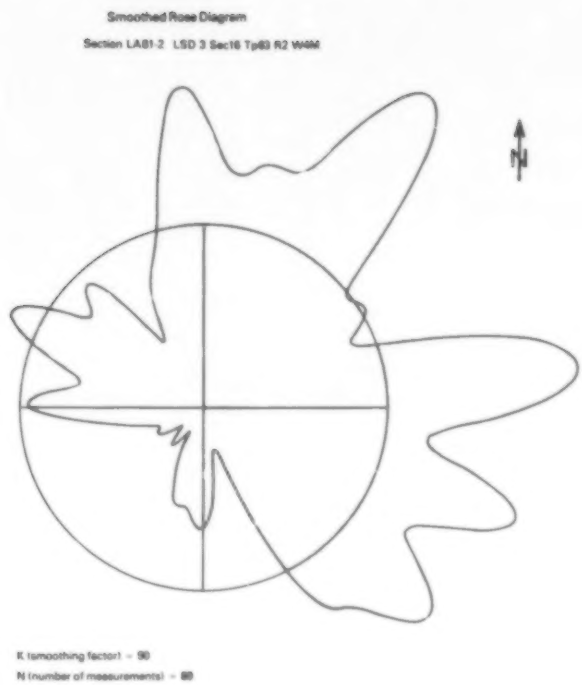


Figure 53. Pebble orientations in the diamicton of the Reita Lake Member.

eastern part of the map area. Within these highlands the member consists in part of stratigraphically older till, mainly the Marie Creek till, that has been displaced by glacial thrusting. In the Wolf and Primrose highlands for example, more than 60 m of the Marie Creek till has been displaced and mantled with a thin (less than 3 m) to discontinuous cover of the Reita Lake Member (figure 55; and Andriashek and Fenton 1979, test holes T1 and 77SR33). Similarly, thick masses of the Marie Creek till have been thrust from the bottom of Marie Lake and deposited as an intact slab on top of the Reita Lake diamicton in the Marie Highland (Andriashek and Fenton 1979, test hole T42).

Differentiation from other units

The differentiation between the Reita Lake Member and Hilda Lake Member is discussed in the previous section.

The Reita Lake Member is differentiated from the Kehiwin Lake Member by the following: (1) the Reita Lake Member has a darker gray brown color, compared to the olive brown color of the Kehiwin Lake Member; (2) the Reita Lake Member has more clay (figure 18); (3) the Reita Lake Member has marginally more igneous and metamorphic rock and less abundant quartz in the very coarse sand (figure 18); and (4) glacially streamlined features on the surface of the Reita Lake Member are oriented in a southwestern direction whereas those of the Kehiwin Lake Member are oriented in a southern direction (figure 47).

The Reita Lake Member is geographically and stratigraphically separated from the Vilna Member by the Kehiwin Lake Member (figure 10, cross section N2-N2'). The orientation of the glacially streamlined features on the surface of the Reita Lake Member is perpendicular to the orientation of those features on the surface of the Vilna Member (figure 47).

The Reita Lake Member is differentiated from the Marie Creek Formation by the following: (1) the Reita Lake Member has a dark gray brown oxidized color, which contrasts with the olive brown oxidized color of the Marie Creek Formation (plate 4); (2) the Reita Lake Member has an unfractured to slightly fissile structure compared to the iron-oxide stained and highly fractured structure of the Marie Creek till; (3) the Reita Lake Member has more clay and less sand, particularly very coarse sand (figure 18); and (4) the Reita Lake Member has considerably less carbonate in both the very-coarse-sand and silt-clay fractions (figure 18).

The Reita Lake Member is differentiated from the Bonnyville Formation by the abundance of clay, and the abundance of igneous and metamorphic rock in the very-coarse-sand fraction (figure 18).

Nature of contacts

Lower contact

The contacts between the Reita Lake Member and the top of the Hilda Lake Member, and between the Reita Lake Member and the Sand River Formation are discussed in the previous sections.

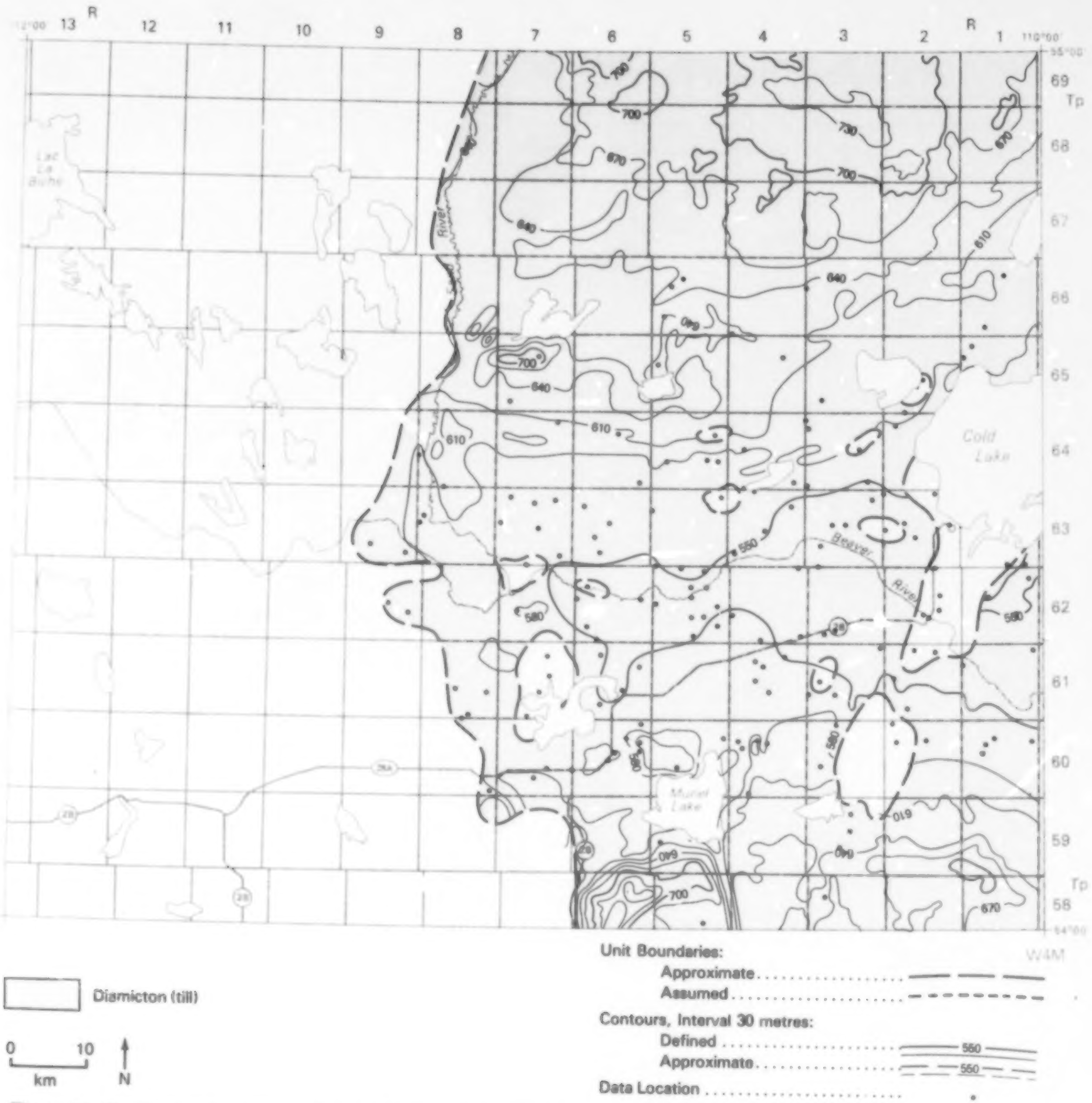
The Reita Lake Member generally has a sharp and well-defined contact with the underlying Marie Creek Formation. Locally, a boulder concentration lies along this contact. In a few places gradational contacts are indicated by an increase of carbonate rock with depth in the Reita Lake Member (Andriashek and Fenton 1979, test holes T5 and T38). The contact can be difficult to establish in places where glacial thrusting has displaced some or all of the underlying Marie Creek Formation and incorporated this material into the Reita Lake Member.

On the basis of the widespread oxidized zone in the upper part of the Marie Creek Formation, the contact with the Reita Lake Member is considered to be disconformable.

Upper contact

The Reita Lake Member lies at the surface over most of the eastern part of the Sand River map area, except where it is overlain by postglacial sediment (Fenton and Andriashek 1983, in pocket).

The contact between the Reita Lake Member and the Kehiwin Lake Member is varied; in places the Reita Lake Member underlies the Kehiwin Lake Member, in other places the two interfinger, forming an ap-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Lac La Biche
River
Cold Lake
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Muriel Lake
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Diamicton (till)
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Unit Boundaries:
Approximate
Assumed
Contours, Interval 30 metres:
Defined
Approximate
Data Location

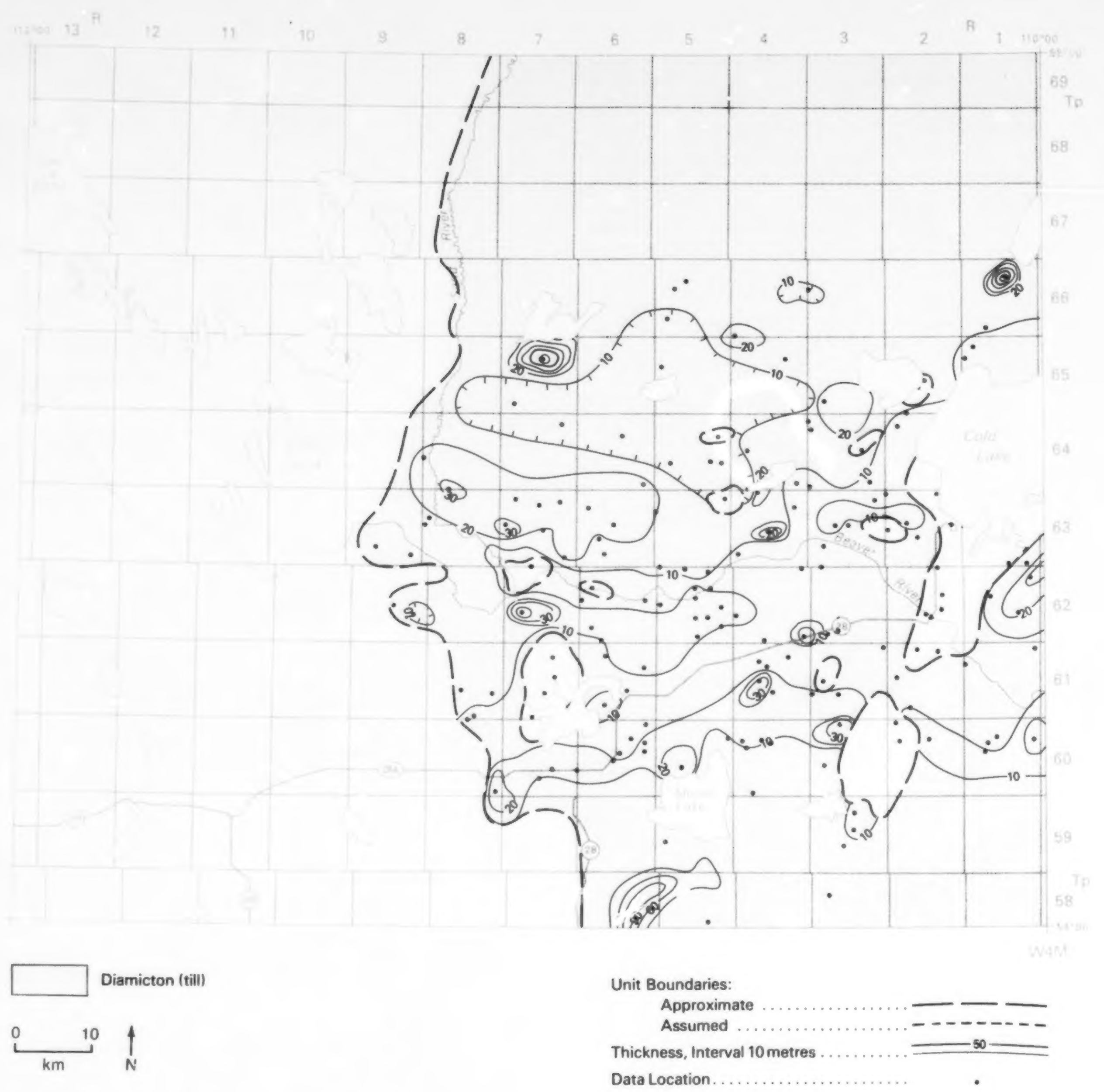
Figure 54. Elevation of the upper surface of the Reita Lake Member.

parent lateral contact (figure 10, cross sections N1-N1' and N2-N2', test holes 77SR18 and 77SR19). In places stratified sediment lies along the contact but the distribution of this sediment is believed to be limited (Andriashek and Fenton 1979, test hole 77SR19). The contact between the two members is more clearly defined on the surface by the intersection of the northeast-southwest oriented glacially streamlined features on the surface of the Reita Lake Member with the north-south oriented glacially streamlined features on the surface of the Kehiwin Lake Member (figure 47).

Origin and differences in the properties of the sediment in the Reita Lake Member

Diamicton of the Reita Lake Member is till deposited by the Primrose Lobe during the Cold Lake Glaciation. Glacial thrusting associated with this advance displaced the Marie Creek till from the major lake basins in the east and transported debris southward to form very high thrust landforms (Fenton and Andriashek 1983, in pocket).

The similarity in orientation of glacially streamlined landforms on the surface of the Reita Lake and Hilda Lake members, as well as the gradational contact be-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Cold Lake
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Diamicton (till)
0
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km
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Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 55. Thickness of diamicton in the Reita Lake Member.

tween the two, indicates that both members were likely deposited by the same ice-lobe. However, stratigraphic and geomorphic evidence supports multiple advances of the Primrose Lobe. In the east-central part of the map area, stratified sediment locally lies between diamicton of the Hilda Lake and Reita Lake members (Andriashek and Fenton 1979, test holes T6 and T12). If this sediment is in place, it indicates either one of the following: (1) synchronous deposition of glaciofluvial or glaciolacustrine silt and sand with till occurred in subglacial or supraglacial environments; or (2) glaciofluvial or glaciolacustrine sediment was deposited on top of the Hilda Lake till either during the later phase of the first advance, or during the early phases of the second advance, which deposited the Reita Lake till. Geomorphic evidence supports this latter hypothesis. South of Cold Lake, glacially thrust landforms that are composed of the Hilda Lake Member are smoothed and subdued, indicating that they were overridden and remolded by a later glacial advance. As well, a large thrust moraine that appears to have once extended across the entire southern end of

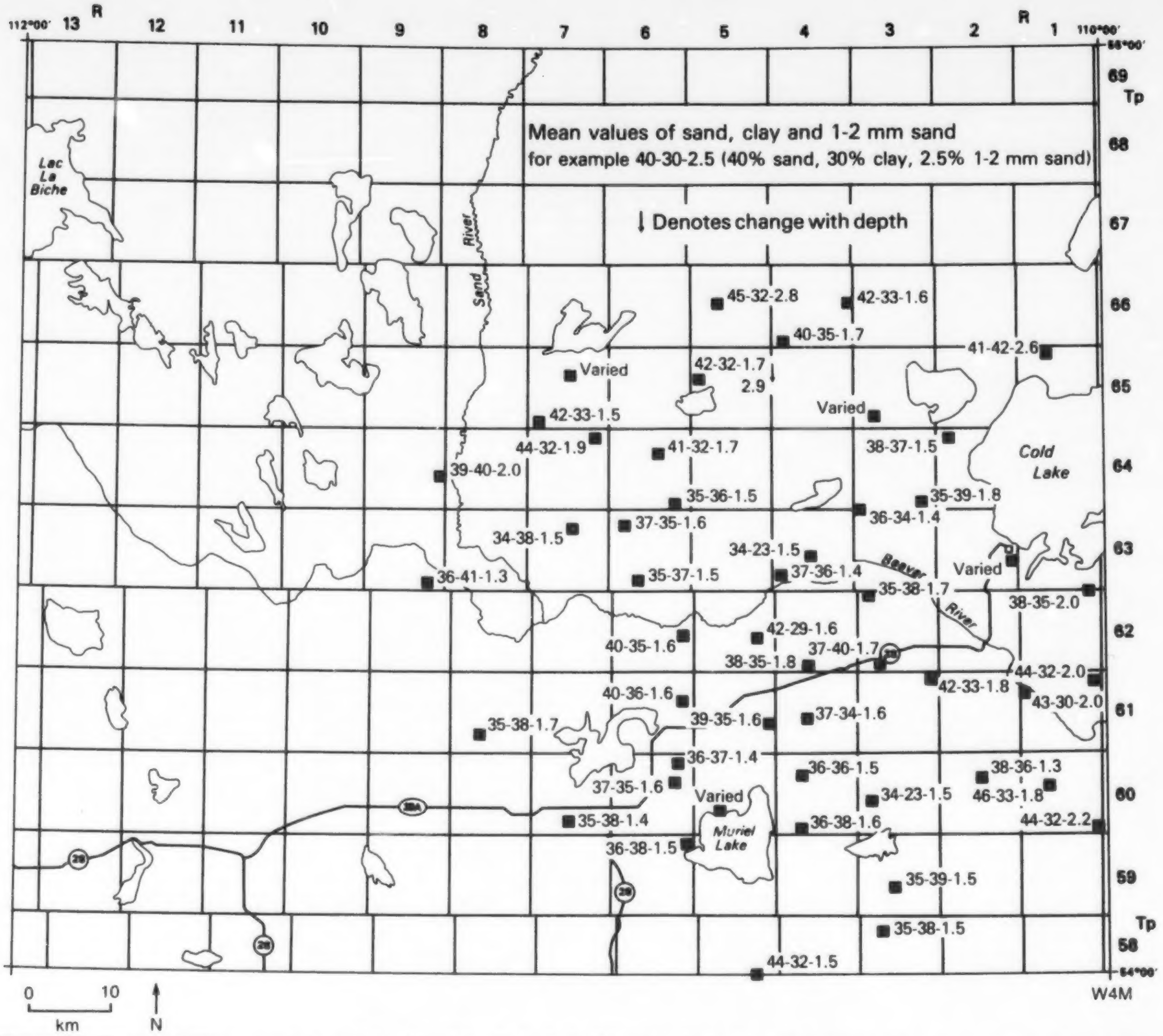

Mean values of sand, clay and 1-2 mm sand
for example 40-30-2.5 (40% sand, 30% clay, 2.5% 1-2 mm sand)
Denotes change with depth
Lac La Biche
Cold Lake
Muriel Lake
Sand River
Beaver River
R
Tp
W4M
0 10 km
N

Figure 56. Regional differences in the grain size of the Reita Lake Member. Note the sandiness of this member in the north and along the eastern boundary of the map area.

Cold Lake, but which is present only along the southeastern part of the lake, was breached and a portion of the moraine was remobilized and deposited along the eastern flank of the readvancing lobe (Fenton and Andriashek 1983, in pocket). Presumably the Reita Lake Member was deposited on top of the Hilda Lake Member during this readvance phase.

Table 8 (appendix B) and figure 56 show that in some areas there are grain size differences in the till of the Reita Lake Member. For example, the till is considerably more sandy within the Beaver Lowlands in Tp 60-61, R 1 and on the uplands to the north. In these areas the Reita Lake till is almost as sandy as the underlying Marie Creek till. In the north the abundance of sand is probably due to sorting of the diamicton by streams on the surface of an ablating glacier. The hummocky collapse topography of the Reita Lake Member in the north (Fenton and Andriashek 1983, in pocket) supports this interpretation. Glacial erosion of the underlying sandy Marie Creek till probably accounts for the abundant sand (including a larger amount of very coarse sand) of the Reita Lake till in the eastern part of the Beaver Lowlands (Andriashek and Fenton 1979, test holes T16, T17, T22, and T72).

Other differences in lithology of the Reita Lake Member relate to different amounts of glacially thrust sediment, mainly Marie Creek till, within the highlands in the eastern half of the map area.

Kehiwin Lake Member

Source of name: Kehiwin Lake, Alberta, located in Tp 58-59, R 7, W 4 Mer, in the south-central part of the Sand River map area, NTS 73L.

Type section: Alberta Geological Survey auger test hole 77SR17, located in LSD 15, Sec 9, Tp 61, R 8, W 4 Mer, in the Sand River map area, NTS 73L (figure 57). At this location the Kehiwin Lake Member overlies the Reita Lake Member of the Grand Centre Formation and is exposed at the surface.

Type area: The area around and south of the town of Glendon, in the south-central part of the Sand River map area, NTS 73L.

Reference sections: Alberta Geological Survey auger test holes 77SR1 (LSD 1, Sec 28, Tp 58, R 8, W 4 Mer), 77SR9 (LSD 16, Sec 7, Tp 60, R 8, W 4 Mer), and 77SR18 (LSD 9, Sec 2, Tp 63, R 9, W 4 Mer).

Description of unit

The Kehiwin Lake Member consists mainly of sandy diamicton. In the southwest corner of the map area this diamicton is locally overlain by stratified sand and gravel. The member has been mapped throughout much of the western half of the map area, mainly from auger test hole samples, but it outcrops only in the central area. The member is oxidized olive brown (2.5Y 4/4) in the upper part but becomes dark olive gray (5Y 3/2) to very dark gray (5Y 3/1) with depth.

The diamicton is sandy, but contains few pebbles. Near the type section numerous lenses and layers of sand are interbedded with the diamicton. The diamicton is typically well-jointed and has a blocky structure and iron oxide and manganese oxide staining along the joint surfaces.

The grain size of the smaller-than-2-mm fraction of the diamicton is about 43% sand, 32% silt, and 25% clay, with about 2% very coarse sand (figure 18). The range in grain size is shown in table 9 (appendix B). The abundance of sand results in a low moisture content of about 10%.

The composition of the very coarse sand is about 62% igneous and metamorphic rock, 29% quartz, 1% quartzite and quartz sandstone, 3% limestone, 3% dolostone, and 1% local rock (figure 18). The range in composition is shown in table 9 (appendix B).

Calcareous material makes up about 8% of the silt-clay fraction (calcite/dolomite ratio = 0.32, figure 18).

Only one sample of the member was analyzed for clay minerals and that contained about 60% illite, 20% kaolinite, 15% smectite, and 5% chlorite (appendix C).

Glacially streamlined landforms on the surface of the Kehiwin Lake Member have a characteristic north-south orientation (figure 47).

Distribution, thickness, and topography

The Kehiwin Lake Member outcrops along an approximately 20-km-wide strip in the central part of the map area, extending from the Seibert Upland in Tp 69, south to the Kehiwin Plateau in Tp 58 (figure 58). The member extends southwest in the subsurface to the Vilna and Saddle plains and the Cache Upland (figure 10, cross sections E4-E4' and N1-N1'). The eastern boundary of the member essentially parallels the Sand River in the north and Kehiwin Lake in the south. The top of the member ranges in elevation from as high as 850 m within the Heart Highland to as low as 590 m within the Kehiwin Plateau (figure 58).

The Kehiwin Lake Member is one of the thickest stratigraphic units in the map area, averaging more than 30 m over most of its extent (figure 10, cross sections N1-N1'and N2-N2'; and figure 59). The member ranges in thickness from as much as 40 m in Tp 60-63, R 9, to as little as 3 m near the reference section in Tp 60, R 8. The member is believed to thin along both the eastern edge where it overlies the Reita Lake Member and along the western edge where it is overlain by the Vilna Member.

The sand and gravel that overlies the diamicton in the southwest corner of the map area is generally less than 7 m thick. It appears to lie within a poorly defined meltwater channel eroded onto the surface of the diamicton of the Kehiwin Lake Member (figure 10, cross section E4-E4').

Differentiation from other units

The differentiation between the Kehiwin Lake Member and the Reita Lake Member is discussed in the previous section. The Kehiwin Lake Member is differentiated from the Vilna Member by the following: (1) the Kehiwin Lake Member is overlain by the Vilna Member in the west (figure 10, cross section N1-N1'); (2) the Kehiwin Lake Member is considerably more sandy (figure 18); (3) the Kehiwin Lake Member contains more quartz and less igneous and metamorphic rock (figure 18); (4) the Kehiwin Lake Member has a lighter olive brown color; and (5) glacially streamlined landforms on the surface of the Kehiwin Lake Member have a north-south orientation, in contrast to the northwest-southeast oriented features on the surface of the Vilna Member (figure 47).

The Kehiwin Lake Member may be difficult to differentiate from the Marie Creek Formation in the field because both units have a similar color, both are sandy, and both have a fractured, blocky structure. However, the Kehiwin Lake Member has fewer pebbles and coarse sand, and it contains significantly less carbonate in the very-coarse-sand and silt-clay fractions (figure 18).

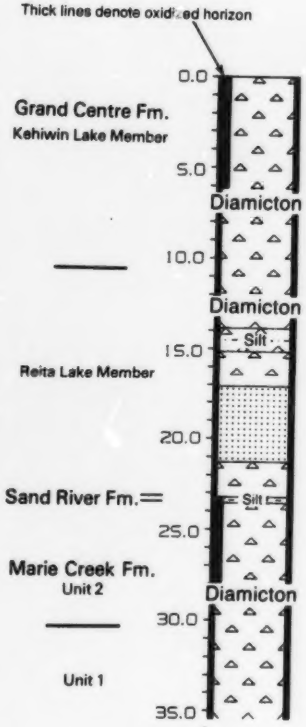
The Kehiwin Lake Member may be more difficult to differentiate from the Bonnyville till, especially in the central part of the map area, because both are sandy, both contain few carbonates, and both have abundant

77SR17

Alberta Geological Survey test hole: 77SR17
Location: NE of LSD 15 Sec 9 Tp 61 R 8 W 4 M NTS: 73L

Elevation: 1900 ft, 579 m
Date drilled: August 8, 1977

Logged by: L. Andriashek.


Thick lines denote oxidized horizon
Grand Centre Fm.
Kehiwin Lake Member
Reita Lake Member
Sand River Fm.
Marie Creek Fm.
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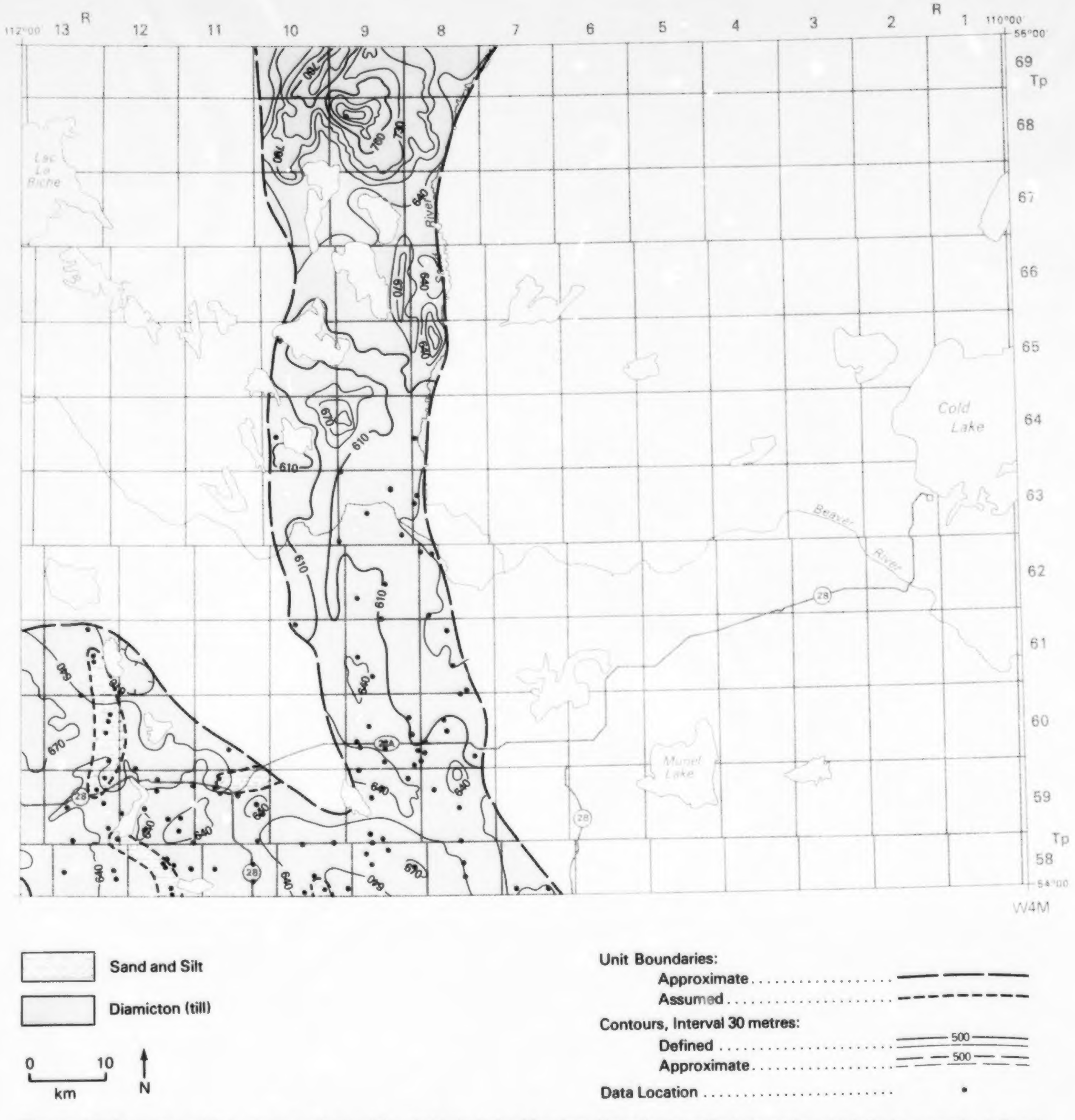
Depth (m)	Grain Size Properties					Silt and Clay Carbonate Content			1-2 mm Sand Petrology							
	Sand % >62.5μm	Silt %	Clay % <4μm	1-2 mm Sand %	Moisture %	CO_2 (cm³)	CO_3 %	Calcite / Dolomite	Igneous Metamorphic %	Quartz %	Quartzite Quartz Sandstone %	Limestone %	Dolostone %	Local %	Other	Total number of grains
1					8				70	22	7	0	1	1	0	364
2	44	26	30	1.1	13				54	27	6	6	6	1	0	521
3	46	26	29	1.1	12				55	25	5	7	7	1	0	560
4	46	26	28	1.3	11				57	25	5	6	6	2	0	420
5	46	26	29	1.2	10				58	26	5	5	4	1	0	414
6	40	27	34	1.1	10				56	27	3	4	3	2	6	476
7	37	27	36	1.3	10				65	25	2	4	1	3	1	392
8	38	26	36	2.3	10				55	24	2	2	5	1	11	333
9	42	27	32	1.9	9				46	21	2	2	5	2	0	448
10	41	27	32	1.7	9				56	22	2	0	3	1	17	441
11					11				76	17	2	1	2	1	0	226
12	37	23	40	1.5	12				67	24	1	3	3	1	1	525
13					12				70	22	2	2	3	1	0	362
14	33	34	34	1.8	8				62	19	1	2	16	1	0	411
15					8				67	25	2	2	4	0	0	441
16	32	29	40	1.4	9				65	24	2	3	5	0	0	351
22	39	25	37	1.7	9				63	26	1	4	6	0	0	377
23	35	27	37	0.9	9				73	25	0	0	1	0	0	470
24					19											
25					10				57	15	0	4	21	2	0	344
26	33	24	43	2.3	10				65	19	1	2	12	2	0	498
27	36	27	37	2.6	9				65	18	1	4	11	1	1	515
28	37	30	33	2.6	8				59	19	1	4	17	1	0	538
29	39	30	31	2.4	8				60	16	0	3	19	1	1	515
30	40	32	29	2.4	8				47	24	0	2	12	2	13	332
31	36	22	42	1.8	9				60	29	0	3	4	1	3	453
32	35	21	44	1.8	9				61	26	0	3	8	2	0	428

Figure 57. Type section of the Kehiwin Lake Member of the Grand Centre Formation. Alberta Geological Survey test hole 77SR17.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58
W4M
Lac La Biche
Cold Lake
Beaver River
Muriel Lake
28
610
640
670
730
760
780
Sand and Silt
Diamicton (till)
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Contours, Interval 30 metres:
Defined
Approximate
500
Data Location

Figure 58. Elevation of the upper surface of the Kehiwin Lake Member. Note the stratified deposits which lie in a poorly defined channel on the surface of the diamicton in Tp 58-61, R 12-13.

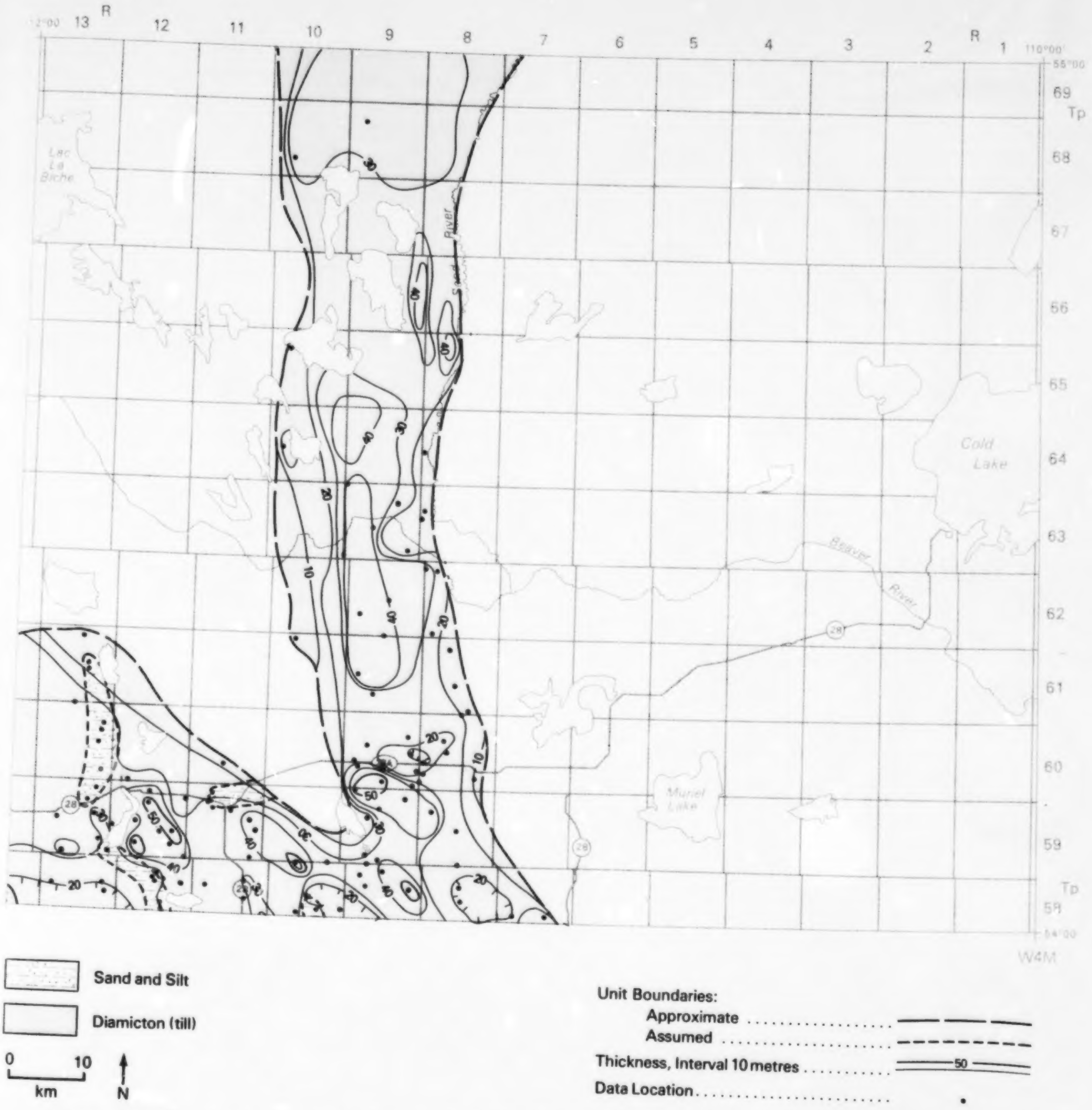
quartz in the very-coarse-sand fraction (figure 9, cross section E3-E3'; and figure 18). However, in the central part of the map area the Kehiwin Lake Member generally contains less very coarse sand (figure 18). In the west the opposite is true; the Kehiwin Lake Member is more sandy than the Bonnyville Formation.

Nature of contacts

Lower contact

The contact between the Kehiwin Lake and Reita Lake members was discussed previously.

The Kehiwin Lake Member has generally a sharp contact with both the underlying Sand River and Marie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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
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W4M
Sand and Silt
Diamicton (till)
0
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km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
Data Location

Figure 59. Total thickness of diamicton and stratified sediment in the Kehiwin Lake Member. Note the widespread thick deposits near the eastern boundary of the member.

Creek formations (Andriashek and Fenton 1979, test hole 77SR16). In the southwest, where the Kehiwin Lake Member directly overlies the Bonnyville Formation, the contact is sharp and well-defined by both the analytical data (Andriashek and Fenton 1979, test hole 77SR1), and the resistance logs (figure 10, cross section E4-E4', test hole E439). The contact differs in the south-central part of the map area, Tp 58-60, R 8-10, where the grain sizes of both units are similar. Here, both sharp and gradational contacts are recognized (Andriashek and Fenton 1979, test holes 77SR2 and 77SR3).

Upper contact

The Kehiwin Lake Member is exposed along a narrow band in the central part of the map area but in the southwest it is buried by the Vilna Member. For the most part this contact is sharp and well-defined (Andriashek and Fenton 1979, test holes 77SR3 and 77SR15). The contact is most easily defined where stratified sediment lies between the diamicton of the two units (figure 10, cross section E4-E4'; and Andriashek and Fenton 1979, test holes 77SR3, 77SR7, and 77SR15). In the central part of the map area the two members interfinger to form a gradational lateral contact (Andriashek and Fenton 1979, test hole 77SR16).

Origin and differences in the properties of the sediment in the Kehiwin Lake Member

Diamicton of the Kehiwin Lake Member is till deposited by the Seibert Lobe during the Cold Lake Glaciation. On the basis of orientation of glacially streamlined features, the Seibert Lobe advanced due south in the central part of the map area (figure 47). Glacial thrusting associated with the Seibert advance eroded the Spencer, Touchwood, Seibert, and possibly Pinehurst lake basins.

It is almost certain that the eastern margin of the Seibert Lobe was in contact with the southwestward flowing Primrose Lobe. Evidence to support this consists of southwest oriented flutes on the surface of the Reita Lake Member that curve southward in Tp 61, R 8, indicating that the southwestward flowing ice was deflected by ice flowing from the north (figure 47). Not only were the two lobes confluent for some time but the westward advance of the Primrose Lobe was restricted by the Seibert Lobe. This confluence prevented the Seibert Lobe from flowing eastward into the topographically lower Beaver Lowlands. Although the contact between the Primrose and Seibert lobes is generally well defined by the surface morphology (Fenton and Andriashek 1983, in pocket), ice from these two lobes must have interfingered, as shown by the interfingering gradational contact of the Kehiwin Lake and Reita Lake tills (Andriashek and Fenton 1979, test holes 77SR18 and 77SR19).

The southward flow of the Seibert Lobe extended across the entire western half of the map area and into the Tawatinaw and Vermilion map areas. This conclusion is based on the presence of the sandy Kehiwin Lake till in the extreme southwest corner, the buried north-south oriented glacial flutes due south of Vilna in Tp 59, R 13 (figure 47), and the series of east-west oriented thrust ridges in the moraine within the Whitefish Lake Highland and in the moraine south of Saddle Lake (Fenton and Andriashek 1983, in pocket), all of which indicate glacial flow southward.

The wastage of the Seibert Lobe was marked by the deposition of glaciofluvial sand and gravel within a poorly defined channel in the far southwest corner of the map area (figure 58). These stratified deposits were later buried by till of the Vilna Member during the last glacial event in the area.

Grain size properties within the Kehiwin Lake till show no significant regional differences or trends (figure 60). Differences are evident, however, in the very-coarse-sand composition. In test hole 77SR4 the till contains about 66% igneous and metamorphic rock and 27% quartz, whereas in nearby test hole 77SR7 the till contains only 57% igneous and metamorphic rock, and as much as 35% quartz, a difference of almost 10% (table 9, appendix B). This local abundance of quartz makes the composition of the very coarse sand of the Kehiwin Lake till very similar to that of the underlying Bonnyville till. This supports the hypothesis that the Kehiwin Lake till was derived in part from the erosion of the underlying Bonnyville till.

Vilna Member

Source of name: Town of Vilna, Alberta, located in Tp 59, R 13, W 4 Mer, in the southwest corner of the Sand River map area, NTS 73L.

Type section: Alberta Geological Survey auger test hole 77SR7, located in LSD 16, Sec 29, Tp 59, R 11, W 4 Mer, in the Sand River map area, NTS 73L (figure 61). At this location the Vilna Member overlies the Kehiwin Lake Member of the Grand Centre Formation and is exposed at the surface.

Type area: The area southeast of the type section, within the Ashmont and Mallaig regions, Tp 58-59, R 9-11, in the Sand River map area, NTS 73L.

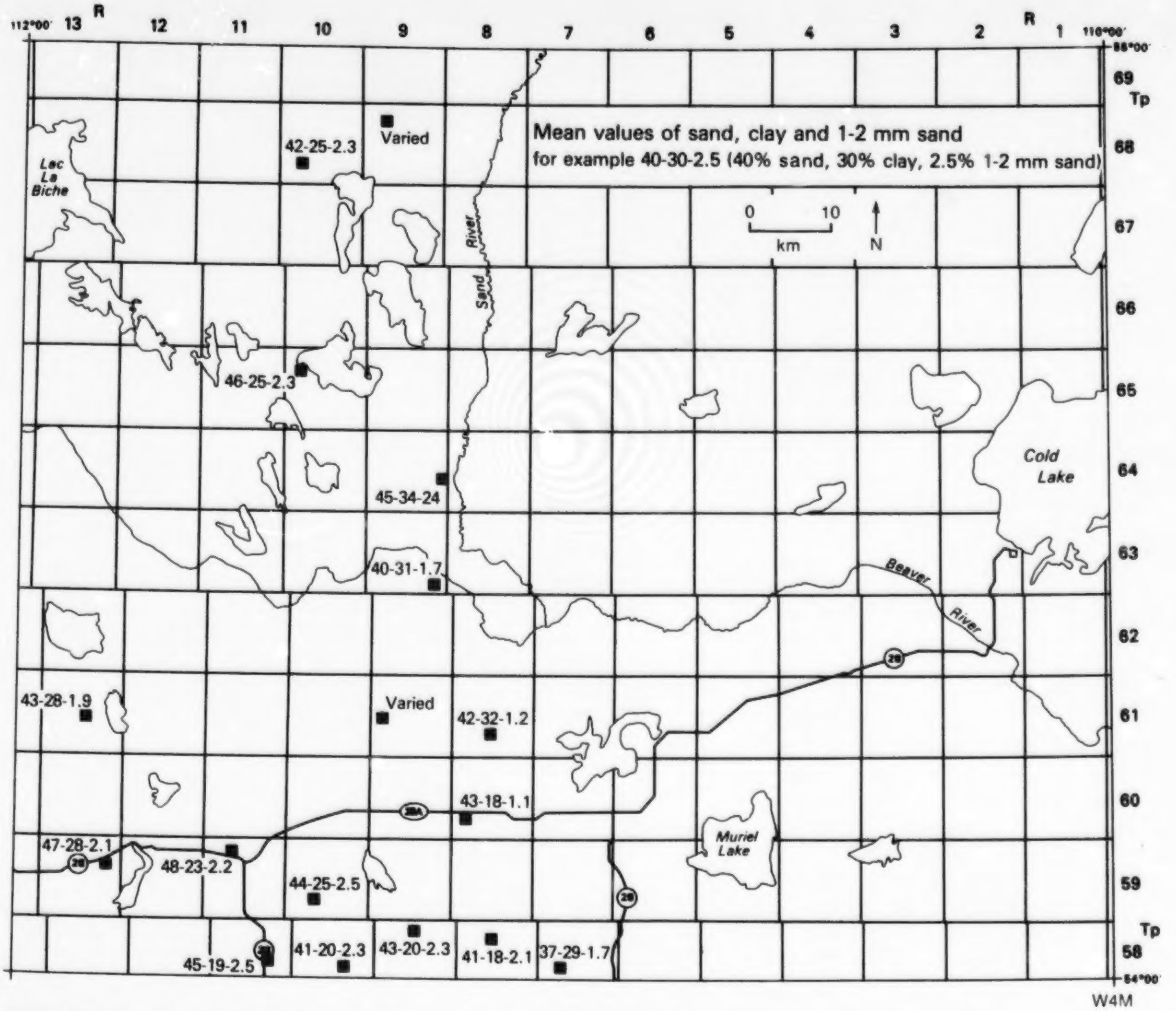
Reference sections: The top of the member is exposed in a road cut in LSD 4, Sec 29, Tp 61, R 10, W 4 Mer. Complete sections of the member are mapped in Alberta Geological Survey auger test holes 77SR3 (LSD 16, Sec 10, Tp 58, R 10, W 4 Mer), 77SR4 (LSD 13, Sec 14, Tp 58, R 11, W 4 Mer), 77SR10 (LSD 1, Sec 33, Tp 58, R 9, W 4 Mer), and 77SR15 (LSD 9, Sec 15, Tp 61, R 13, W 4 Mer).

Description of unit

The Vilna Member consists of clayey diamicton that locally includes blocks of glacially displaced older sediment. The member is the surface unit in most of the western part of the map area and is mapped from both outcrops and test hole samples. The Vilna Member is oxidized dark gray brown (2.5Y 4/2) in the upper part but becomes very dark gray (5Y 3/1) with depth. The diamicton contains few pebbles and in outcrop is generally unfractured, though in places it has a stratified appearance. The layers generally consist of older sediment that has been glacially displaced and attenuated in the form of layers or beds within the diamicton (plate 6).

The grain size of the smaller-than-2-mm fraction of the diamicton is about 32% sand, 32% silt, and 36% clay, with about 1% very coarse sand (figure 18). The range in grain size is shown in table 10 (appendix B). The abundance of clay results in a moisture content of about 13% and this causes the unit to be soft and easy to penetrate with an auger.

The composition of the very coarse sand is about 64% igneous and metamorphic rock, 28% quartz, less than 1% quartzite and quartz sandstone, 3% lime-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W4M
Mean values of sand, clay and 1-2 mm sand
for example 40-30-2.5 (40% sand, 30% clay, 2.5% 1-2 mm sand)
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10
km
N
Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
42-25-2.3
Varied
46-25-2.3
45-34-24
40-31-1.7
43-28-1.9
Varied
42-32-1.2
43-18-1.1
47-28-2.1
48-23-2.2
44-25-2.5
45-19-2.5
41-20-2.3
43-20-2.3
41-18-2.1
37-29-1.7
28
28A
28
28
36

Figure 60. Regional differences in the grain size of the Kehiwin Lake Member.

stone, 3% dolostone, and 1% locally derived rock (figure 18). The range in composition is shown in table 10 (appendix B).

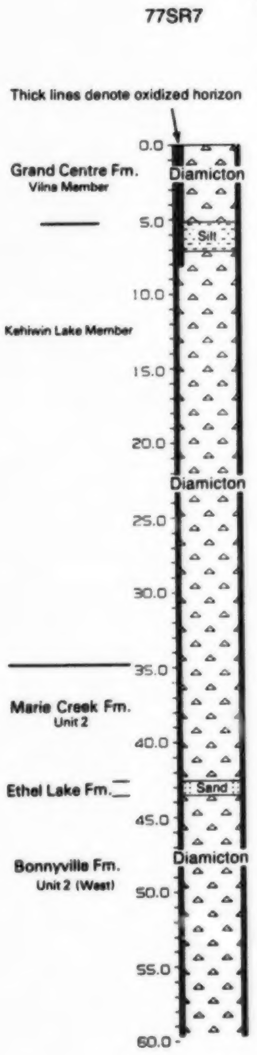
Calcareous material makes up about 11% of the silt-clay fraction (calcite/dolomite ratio = 0.33, figure 18).

The clay minerals of a few samples from one test hole consist of about 55% illite, 20% kaolinite, 15% smectite, and 10% chlorite (appendix C).

Glacially streamlined landforms on the surface of the Vilna Member are well defined and have a northwest-southeast orientation (figure 47).

Distribution, thickness, and topography

The Vilna Member is the surface unit over most of the western part of the Sand River map area (figure 62). It is absent only in a number of isolated areas within Tp 58-60, R 9-13, where the underlying Kehiwin Lake Member is exposed. The top of the Vilna Member ranges in elevation from as high as 700 m within a large glacial ice-thrust moraine in the Garner Upland, to as low as 550 m within the area bordering Lac La Biche. The eastern limit of the member lies essentially along R 10, extending south from Tp 69 to Tp 58. This boundary is not clearly defined, mainly because the Vilna Member is gradational or interfingers with the Kehiwin Lake Member. The surface morphology of the Vilna Member is more useful for establishing the eastern boundary: in the north, the limit is defined by a hummocky, interlobate moraine in the Seibert Upland (Fenton and Andriashek 1983, in pocket); in the south, the limit is defined by the intersection of the northwest-southeast oriented landforms of the Vilna Member with the north-south oriented landforms of the Kehiwin Lake Member. The Vilna Member extends west and


77SR7
Thick lines denote oxidized horizon
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35.0
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45.0
50.0
55.0
60.0
Diamicton
Silt
Diamicton
Sand
Diamicton
Grand Centre Fm.
Vilna Member
Kehiwin Lake Member
Marie Creek Fm.
Unit 2
Ethel Lake Fm.
Bonnyville Fm.
Unit 2 (West)

Alberta Geological Survey test hole: 77SR7
Location: NE of LSD 16 Sec 29 Tp 59 R 11 W 4 M NTS:73L

Elevation: 2130 ft, 649 m
Date drilled: July 27, 1977 Logged by: L. Andriashek.

Depth (m)	Grain Size Properties					Silt and Clay Carbonate Content			1-2 mm Sand Petrology							
	Sand % >62.5μm	Silt %	Clay % <4μm	1-2 mm Sand %	Moisture %	CO_2 (cm³)	CO_3 %	Calcite/Dolomite	Igneous Metamorphic %	Quartz %	Quartzite Quartz Sandstone %	Limestone %	Dolostone %	Local %	Other	Total number of grains
1					23				68	29	3	0	0	1	0	275
2	27	24	49	1.2	15				64	31	1	2	1	1	0	143
3	29	30	41	0.0	11				60	35	0	3	2	1	0	347
4	31	32	37	1.3	18				67	20	2	4	4	4	0	51
5	42	27	31	2.1	11				66	30	0	1	2	1	0	294
6					12				56	40	0	3	2	0	0	114
7	47	23	30	2.5	11				61	31	1	2	4	1	0	323
8	49	23	29	2.5	12				58	32	1	4	3	2	0	408
9	50	23	28	2.6	10				57	39	1	0	2	2	0	484
10					10				59	34	1	1	3	2	0	362
11	46	30	24	2.4	11				62	29	1	3	4	1	0	383
12					10				60	32	1	4	1	3	0	390
13	47	32	21	2.0	12				57	34	0	4	4	1	0	308
14					9				57	36	1	0	1	1	0	295
15	49	31	20	2.2	13				57	37	0	3	3	1	0	311
16					10				58	33	1	3	3	1	0	276
17	49	31	21	2.0	9				60	31	0	4	3	2	0	324
18					12				64	30	0	1	3	2	1	312
19	50	27	24	2.3	10				61	36	0	1	0	1	0	267
20					10				59	32	0	3	3	3	0	354
21	48	27	25	2.1	11				54	37	0	3	3	2	0	441
22					11				55	37	0	3	3	1	0	368
23	40	30	24	2.0	10				55	37	0	3	2	2	0	37
24					11				53	38	1	4	4	2	0	333
25	47	28	25	1.8	12				55	38	1	2	2	2	0	367
26					12				58	33	1	5	2	1	0	300
27	49	27	24	1.8	11				56	35	1	4	3	1	0	433
28					11				58	36	1	3	1	1	0	438
29	48	28	24	1.8	10				56	33	1	4	5	1	0	424
30					11				54	39	1	4	3	0	0	442
31	46	31	23	2.2	11				58	34	1	5	1	2	0	434
32					11				55	38	1	4	2	1	0	452
33	47	30	23	2.4	11				53	39	1	3	3	1	0	442
34					10				55	35	1	3	5	1	0	472
35	50	31	19	2.5	10				64	29	1	1	4	1	0	286
36					10				62	30	1	2	4	1	0	472
37	43	28	29	2.2	9				63	29	1	2	4	1	0	500
38					11				59	33	2	2	3	1	0	374
39	40	28	33	2.1	10				62	26	2	2	7	2	0	383
40					10				63	28	1	2	6	1	0	376
41	40	30	30	2.1	11				62	27	1	3	6	2	0	453
42					10				63	23	2	4	7	2	0	325
44	29	40	31	1.4	13				49	36	1	7	4	2	0	288
45					13				55	42	0	5	5	3	1	266
46	33	38	30	1.6	12				57	35	1	4	0	3	0	273
47					12				54	32	0	5	4	4	1	377
48	39	35	26	1.2	13				51	36	3	2	4	5	0	371
49					12				51	40	1	3	3	2	0	410
50	33	35	32	1.4	12				52	40	1	4	2	2	0	365
51					13				49	40	1	4	3	2	0	263
52	31	33	36	1.3	13				52	38	0	5	3	2	1	271
53					11				57	36	1	2	1	2	0	332
54	41	31	28	2.1	11				52	38	1	4	4	1	0	424
55					13											
56	39	29	32	1.5	11				56	36	2	3	2	1	0	382
57					12				52	36	1	6	2	3	0	352
58	38	38	24	1.6	12				56	37	1	2	3	2	0	358
59	39	32	30	1.5	12				61	32	1	2	2	1	0	324
60	38	39	25	1.4	11				60	33	1	3	2	2	0	323

Figure 61. Type section of the Vilna Member of the Grand Centre Formation. Alberta Geological Survey test hole 77SR7.

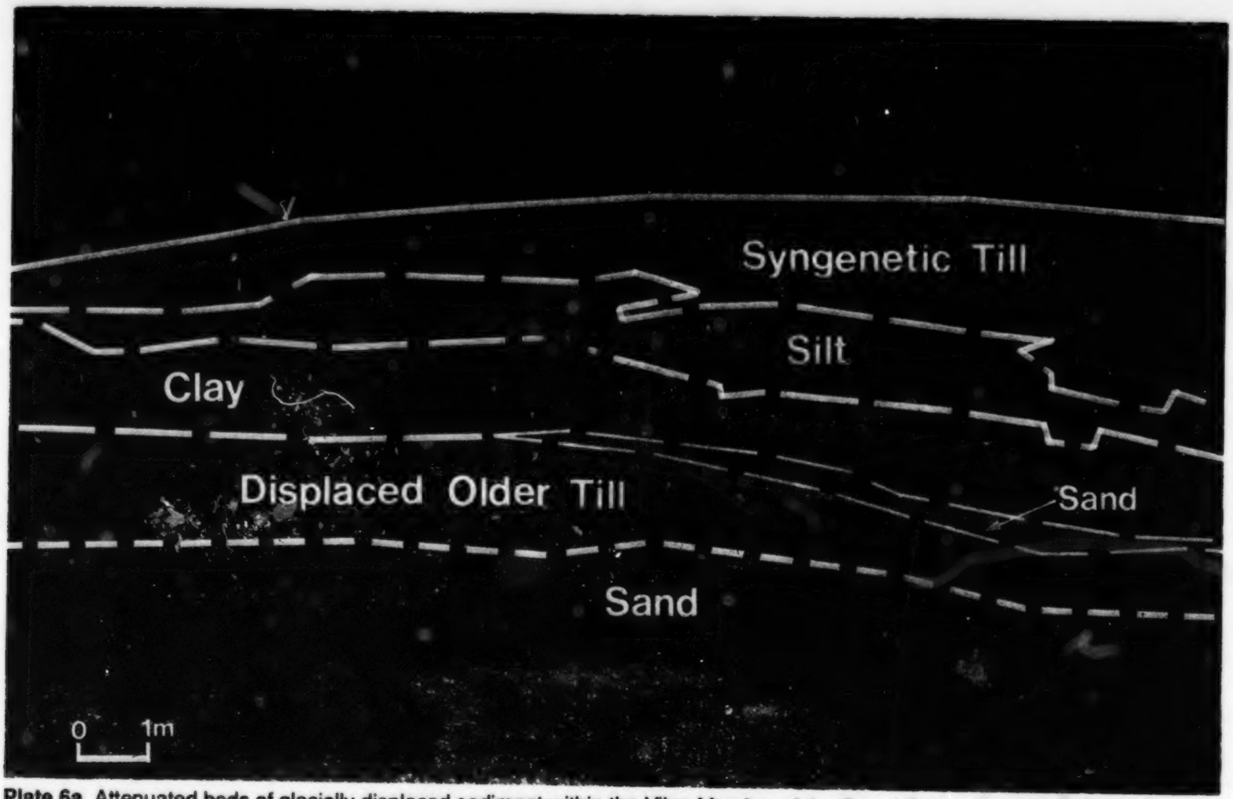

Syngenetic Till
Silt
Clay
Displaced Older Till
Sand
Sand
0 1m

Plate 6a. Attenuated beds of glacially displaced sediment within the Vilna Member of the Grand Centre Formation. Section LA77-114 (LSD 15, Sec 13, Tp 69, R 13, W 4 Mer).

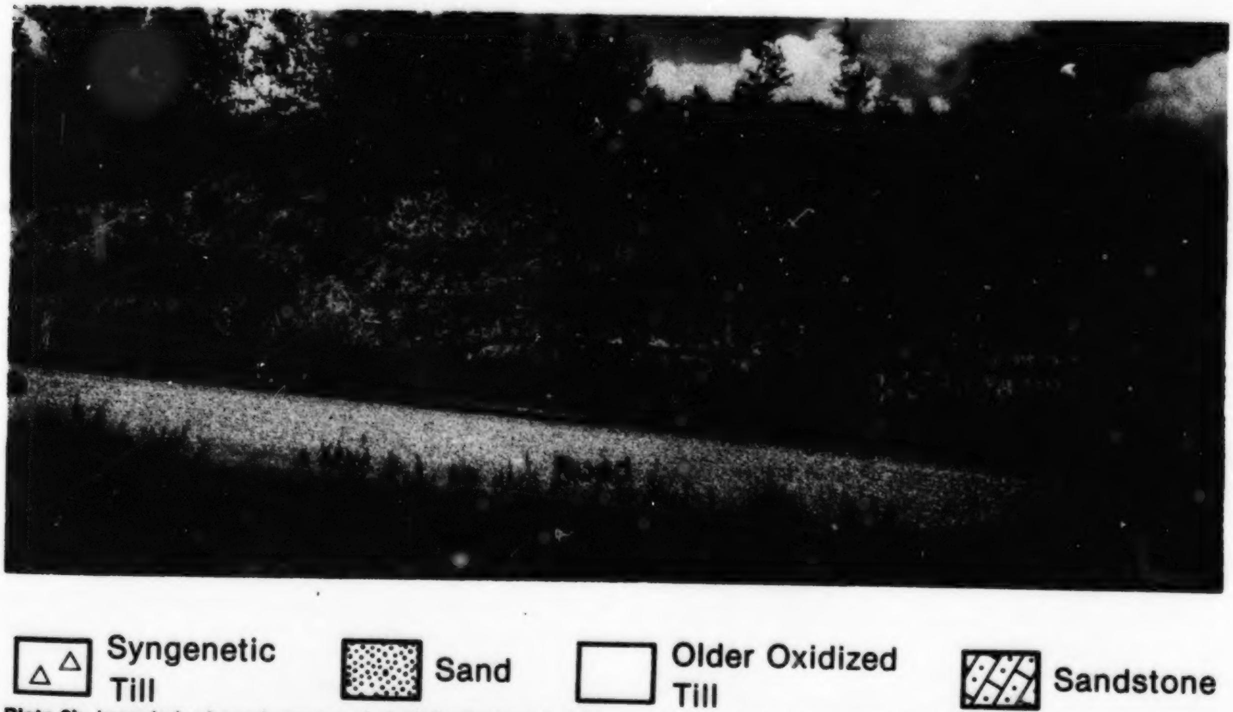
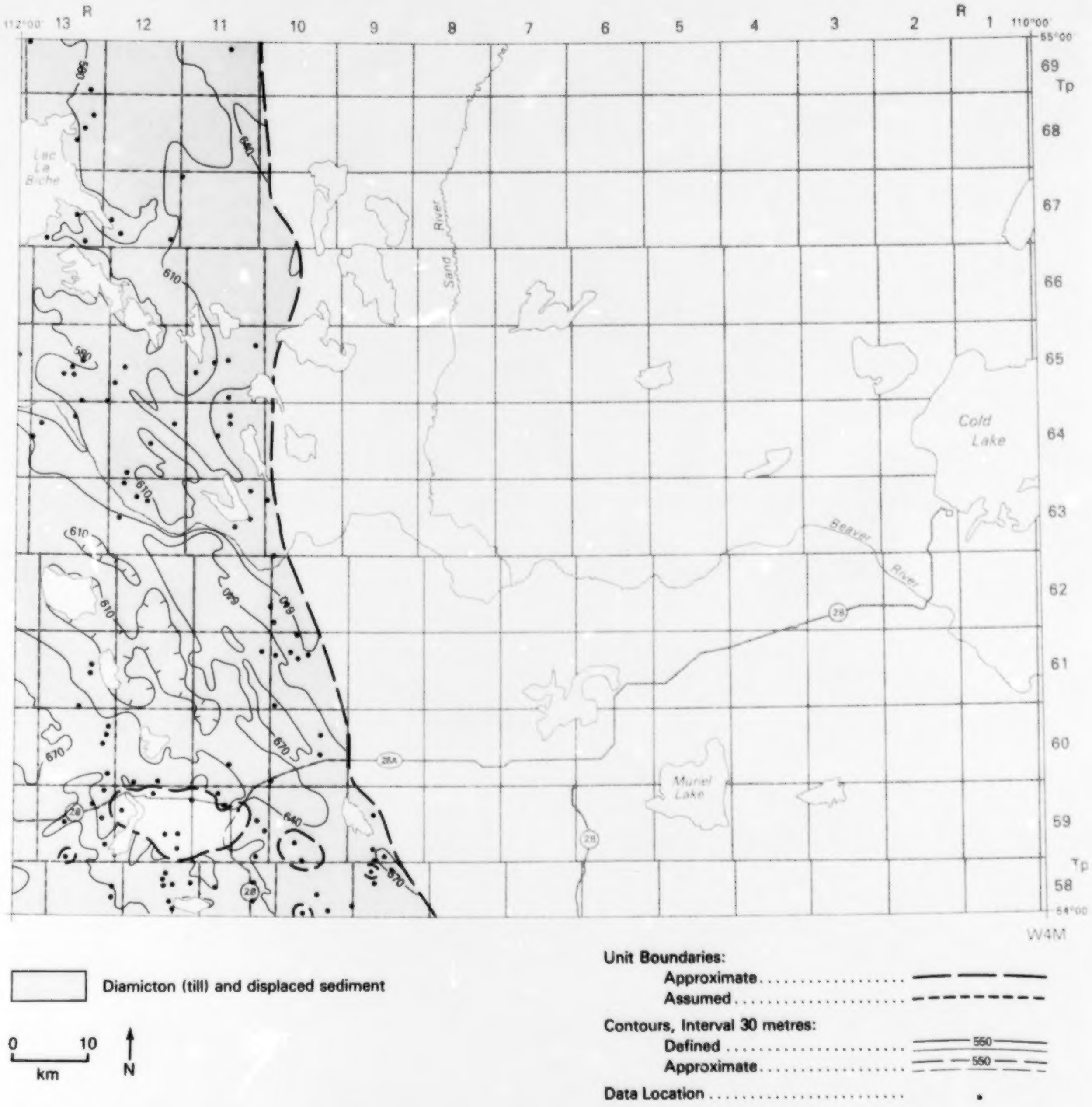

Syngenetic Till
Sand
Older Oxidized Till
Sandstone

Plate 6b. Irregularly shaped masses of glacially displaced sediment within the Vilna Member of the Grand Centre Formation. Section MF77-137 (LSD 14, Sec 24, Tp 59, R 10, W 4 Mer).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59
58
Tp
W4M
Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
28A
610
580
640
670
Diamicton (till) and displaced sediment
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Contours, Interval 30 metres:
Defined
Approximate
560
550
Data Location

Figure 62. Elevation of the upper surface of the Vilna Member.

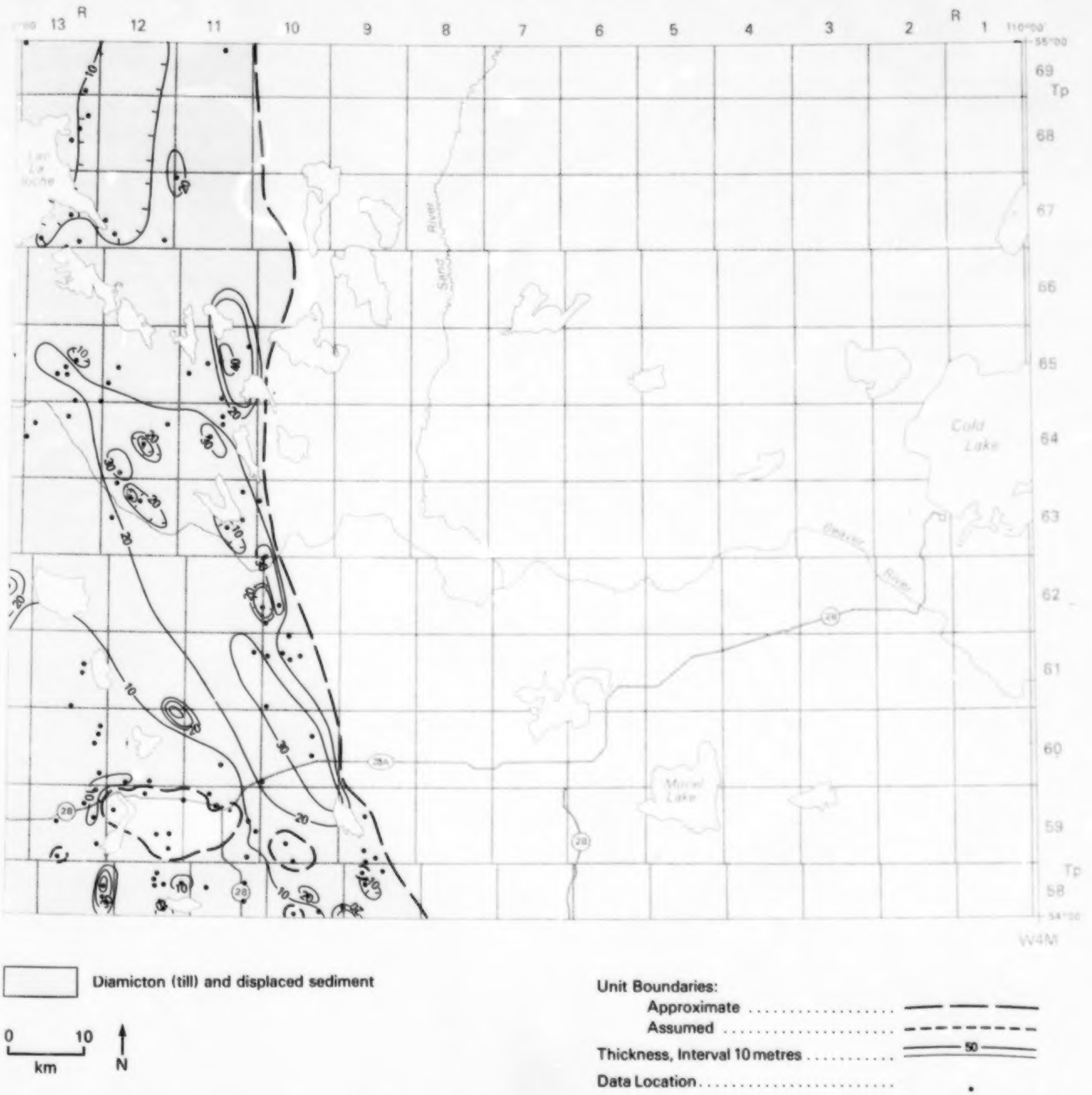
south out of the study area and into the Tawatinaw and Vermilion map areas (figure 10, cross sections E4-E4' and N1-N1').

The Vilna Member is thickest (40 m) within isolated areas in the southwest and along the southeast border of the unit (figure 63). Thin sediments of the Vilna Member (less than 10 m) are found in the area bordering Lac La Biche near Imperial Mills in Tp 67-69, R 12-13, and in the extreme southwest corner of the map area in Tp 58-61, R 13-14, where the member forms a thin to discontinuous cover overtop the Kehiwin Lake Member (figure 10, cross section E4-E4'; and figure 63).

Differentiation from other units

The Vilna Member overlies the Kehiwin Lake Member in the southwest corner and older formations in the west-central and northwest corners. The differentiation between the Vilna and Kehiwin Lake Members has been discussed previously.

The Vilna Member is differentiated from the Marie Creek Formation on the basis of stratigraphic position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63
62
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59
Tp
58
54°00'
W4M
Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
28A
10
20
30
40
Diamicton (till) and displaced sediment
0
10
km
N
Unit Boundaries:
Approximate
Assumed
Thickness, Interval 10 metres
50
Data Location

Figure 63. Thickness of diamicton and glacially displaced sediment in the Vilna Member. Note the thick deposits that extend from Lac La Biche, southeast to Tp 59, R 10.

and composition of the very coarse sand. The Vilna Member overlies the Marie Creek till and locally the two are separated by stratified deposits of the Sand River Formation. The Marie Creek till contains more calcareous material than the Vilna Member (figure 18). The differentiation between the two units is more difficult in the west-central part of the map area where the distinctive upper dolomitic facies of the Marie Creek till has been incorporated into the Vilna Member as intact bodies of glacially displaced material (figure 10, cross section N1-N1', test hole 77SR12; and Andriashek and Fenton 1979, test holes 77SR8, 77SR20, and 77SR22).

The Vilna Member directly overlies the Bonnyville Formation in only a few places in the west (figure 10, cross section E4-E4'). The two are difficult to differentiate because locally their grain size and very-coarse-sand compositions are similar (Andriashek and Fenton 1979, test hole 77SR21). The differentiation is easier in the northwest where stratified sediment of the Sand River Formation commonly separates the two and where the Bonnyville Formation is sandier and has a lighter olive brown color (Andriashek and Fenton 1979, test holes 77SR27 and 77SR28).

Nature of contacts

Lower contact

The contact between the Vilna and Kehiwin Lake members is discussed in the previous section.

The Vilna Member has a sharp contact with the top of the Sand River Formation. The contact between the Vilna Member and the Marie Creek Formation may be difficult to establish because in the west the two units have a similar grain size. Glacial incorporation of the underlying Marie Creek Formation makes the undisturbed contact between the two difficult to recognize.

The contact between the Vilna Member and the Bonnyville Formation is recognized mainly on the basis of color. The top of the Bonnyville Formation in the west is commonly oxidized olive brown whereas the base of the Vilna Member is unoxidized and dark gray.

Upper contact

The surface of the Vilna Member is presently exposed, except for small areas where it is buried by postglacial stratified sediment (Fenton and Andriashek 1983, in pocket).

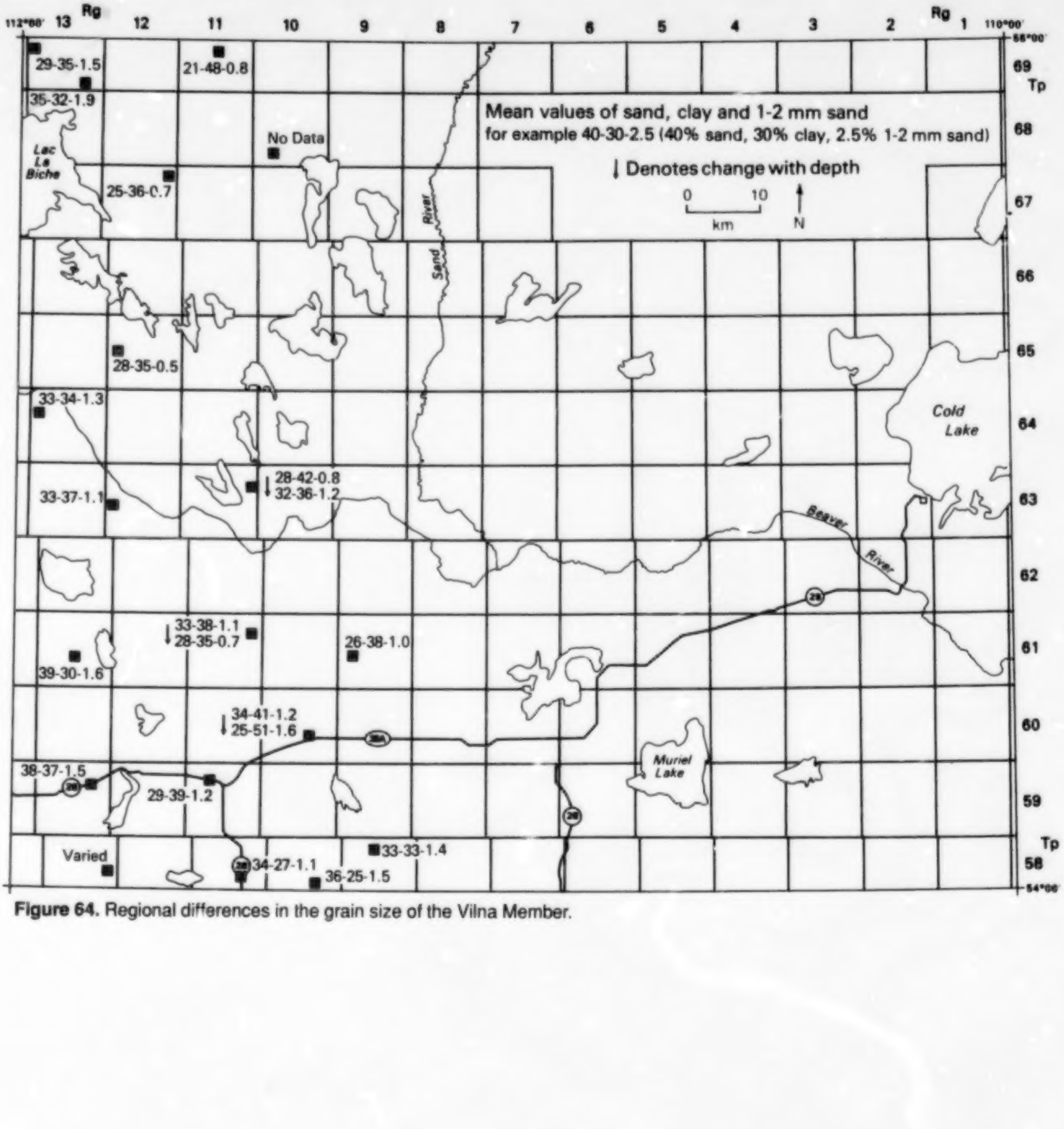
Origin and differences in the properties of the sediment in the Vilna Member

Diamicton of the Vilna Member is till deposited by the Lac La Biche Lobe during the latter phases of the Cold Lake Glaciation. The Lac La Biche Lobe advanced from the northwest as an ice stream, and is considered to be a remobilization of the retreating margin of the Seibert Lobe. The lobe was strongly erosive along the northeast-facing flank of the Garner and Lac La Biche uplands. This erosion occurred in the form of glacial thrusting that displaced large, intact blocks of the underlying units (Fenton and Andriashek 1983, in pocket). It is concluded that the absence of the Kehiwin Lake Member in most of the western and northwestern parts of the map area can be attributed to this erosion.

The Lac La Biche Lobe probably extended into the far southwest corner in the form of a thin ice cover, rather than a fast-flowing ice stream. Evidence for this is that in the southwest the Vilna Member forms thin, low relief, stagnant-ice landforms, which likely indicates that the ice was also thin and relatively free of debris. As well, the contact between the Vilna and Kehiwin Lake till is sharp and well-defined in the southwest, indicating that the underlying sediments in that area were not eroded by glacial thrusting.

The distribution of glacially streamlined features on the surface of the Vilna Member indicates that the faster flowing and erosive ice stream of the Lac La Biche Lobe probably was restricted by the rise in the regional topography in the southwest (figures 4, 29, and 58) and by the ice mass of the Seibert Lobe to the northeast. Evidence to support confluent flow of the Lac La Biche and Seibert lobes includes: (1) the interfingering to gradational contact between the Vilna and Kehiwin Lake tills in the west-central part of the map area; (2) a hummocky, interlobate moraine, that forms the western part of the Seibert Upland (figure 10, cross section N2-N2'; and Fenton and Andriashek 1983, in pocket); and (3) the deflection southward of southeast oriented flutes on the surface of the Vilna Member by the southerly flowing ice of the Seibert Lobe (figure 47).

The Vilna Member has a wide range of lithologic properties. The clay, as well as most of the grain size differences of the till can be attributed mainly to glacial incorporation of claystone and siltstone (figure 64 and plate 6). Local differences in the amount of incorporated material can make it difficult to correlate the Vilna Member from outcrop to outcrop. This is particularly true in the Garner Upland where much of the member is composed of claystone and siltstone (plate 6b). Along the southeast part of the Garner Upland in Tp 59, R 9, these slabs of displaced claystone and siltstone have been reworked to form diamicton composed almost entirely of well-rounded granules of clay. Significant differences in material within the member are also recognized in the Lac La Biche and Seibert uplands, where slabs of glacially displaced Marie Creek till are common, and north of Lac La Biche, in Tp 67-69, where the member consists of either glacially displaced stratified sediment (plate 6a) or glacially overridden and deformed fluvial sand (Owl River area, Fenton and Andriashek 1983, in pocket). In contrast, in those areas where glacial thrusting did not occur, such as within the Vilna Plain in the southwest, the Vilna Member consists of till with a more consistent grain size and lithic composition.


112°00'
Rg
13
12
11
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7
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5
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3
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69
Tp
68
67
66
65
64
63
62
61
60
59
Tp
58
54°00'
Mean values of sand, clay and 1-2 mm sand
for example 40-30-2.5 (40% sand, 30% clay, 2.5% 1-2 mm sand)
↓ Denotes change with depth
0
10
km
N
29-35-1.5
21-48-0.8
35-32-1.9
No Data
Lac La Biche
25-36-0.7
Sand River
28-35-0.5
33-34-1.3
Cold Lake
33-37-1.1
28-42-0.8
32-36-1.2
Beaver River
33-38-1.1
28-35-0.7
26-38-1.0
39-30-1.6
34-41-1.2
25-51-1.6
28A
38-37-1.5
28
29-39-1.2
Muriel Lake
28
Varied
28
34-27-1.1
33-33-1.4
36-25-1.5

Figure 64. Regional differences in the grain size of the Vilna Member.

History and regional correlations

One of the two main purposes of this study has been to characterize the lithologic properties of the Pleistocene units in the Sand River area for the purpose of defining and correlating stratigraphic horizons throughout the area. This has been accomplished using a variety of methods including outcrop and test hole observations, analytical data, and geophysical techniques. This information together with that from the surficial geology, where applicable, is used to construct the following history.

A sedimentological differentiation of the till types was not feasible in this study for a number of reasons. Firstly, such differentiations require numerous and detailed outcrop observations of pebble fabrics, structures, nature of contacts, and stratified intrabeds within the diamictons. Few outcrops were found in this study area and those that were found revealed only the upper part of the stratigraphic sequence. Secondly, the scope of coverage in the investigation and the time available did not permit detailed mapping of the few outcrops in the area.

In this study the interpretations of the till and intertill stratified units indicate that four major glaciations occurred in the area, each depositing a uniquely different till. This hypothesis forms the foundation for the following proposed Quaternary history, summarized in table 11.

Preglacial history

Two major drainage systems, the Helina and Beverly valleys, developed prior to the glaciation of the Sand River map area. Both rivers drained northeast from the cordillera, depositing quartzitic and chert gravel on the broad valley floors. Salt-and-pepper sand composed mainly of quartz and dark chert derived from the local rock, was later deposited overtop of this gravel. Previous workers (Rutherford 1937; Stalker 1967) called these basal fluvial deposits the "Saskatchewan sand and gravel" which constitute unit 1 of the Empress Formation. Both drainage systems developed over a long period during the Cenozoic and locally stream capture likely occurred, as indicated by the reversed gradients at the eastern and western ends of the Helina Valley in the map area.

The Vegreville, Vermilion, Sinclair, Imperial Mills and possibly St. Paul valleys developed as tributaries to the Beverly and Helina valleys. These had their headwaters in the plains of Alberta, where outcrops of poorly lithified Cretaceous mudstone and sandstone were eroded with much of the sand subsequently deposited on the valley floors.

Glacial history

The till and intertill sequence in the Quaternary stratigraphic record indicates several glaciations, probably as many as four, in the Sand River map area. From oldest to youngest, these are named the Cherry Grove, Fort Kent, Ardmore, and Cold Lake glaciations.

Event one: Cherry Grove Glaciation

Advance phase

The three units of the Empress Formation reflect the transition from sedimentation within a Tertiary drainage system to deposition in a system influenced by the advance of the Cherry Grove Glaciation into the Sand River area. Drainage within these major valleys was blocked even while the Cherry Grove Glacier was some distance northeast of the study area. North of the study area, the Wiau Valley was blocked with ice to the northeast and drainage was diverted south. This eroded the Imperial Mills Valley, which later joined with the Helina Valley. Preglacial sand and gravel of unit 1 of the Empress Formation were eroded from within the Wiau Valley and redeposited on the floor of the Imperial Mills Valley by this diverted water. As the Cherry Grove Glaciation continued, drainage in the Helina Valley was similarly blocked and diverted southeast toward the Beverly Valley, this time eroding the Kikino Valley. Preglacial fluvial deposits were also eroded from the Helina Valley and redeposited on the floor of the Kikino Valley.

A series of ice-ponded lakes developed as a result of the glacial blockage. These lakes reduced the gradients of the preglacial rivers, causing suspended offshore sediment to be deposited overtop the coarser basal sand and gravel. This fine sediment constitutes unit 2 of the Empress Formation.

Further rise of the water ponded within the Beverly Valley caused the drainage to overflow the confining valley walls. This water drained eastward, sequentially eroding the Moore Lake, Big Meadow, Bronson Lake, and Holyoke channels as the glacial margin advanced southward. Preglacial sand and gravel of unit 1 of the Empress Formation were eroded from the floor of the Beverly Valley and deposited along the western segments of the Big Meadow and Bronson Lake channels. Elsewhere, glaciofluvial sand and gravel of unit 3 of the Empress Formation were deposited either overtop unit 2 in the major buried valleys or on the floors of the newly eroded channels. In places, such as along the western end of the Moore Lake Channel and within the Beverly Valley in Tp 59, R 9-10, meltwater flowed off the glacier and deposited sand and gravel higher than the surrounding outwash. The meltwater scoured

Table 11. Summary of geologic events from the late Cretaceous to the Holocene in the Sand River map area.

Quaternary		
Holocene (nonglacial)	Erosion and Deposition	Post Glacial Stratified Deposits
Pleistocene		
Retreat	Deposition and Erosion	Post Glacial Stratified Deposits
Cold Lake Glaciation	Deposition	Grand Centre Formation
Lac La Biche Lobe		– Vilna Member (till)
Seibert Lobe		– Kehiwin Lake Member (till)
Primrose Lobe		– Reita Lake Member (till)
		– Hilda Lake Member (till)
Advance	Deposition	Sand River Formation (clay, silt, sand, gravel)
Nonglacial	Erosion and Weathering	Oxidation of Marie Creek and Bonnyville formations
Retreat	Deposition	Sand River Formation (clay, silt, sand, gravel)
Ardmore Glaciation	Deposition	Marie Creek Formation – Unit 2 (till) – Unit 1 (till)
Advance	Deposition	Ethel Lake Formation (clay, silt, sand, gravel)
Nonglacial	Weathering and Erosion	Oxidation of Bonnyville Formation
Retreat	Deposition	Ethel Lake Formation (silt and clay, some sand, gravel)
Fort Kent Glaciation	Deposition	Bonnyville Formation – Unit 2 (till) – Unit 1 (till and sand, gravel)
Advance	Deposition	Muriel Lake Formation (sand and gravel, some silt, clay)
Nonglacial	Erosion and Weathering	Oxidation of Bronson Lake Formation
Retreat	Deposition	Muriel Lake Formation (sand and gravel, some silt and clay)
Cherry Grove Glaciation	Deposition	Bronson Lake Formation (till and clay)
Advance	Deposition	Empress Formation – Unit 3 (glacial sand and gravel) – Unit 2 (silt and clay)
Tertiary Fluvial	Erosion and Deposition	Empress Formation – Unit 1 (preglacial sand and gravel)
Cretaceous Non marine	Deposition	Belly River Formation (sandstone, siltstone, mudstone)
Marine	Deposition	Lea Park Formation (claystone)

the western end of the Moore Lake Channel deeper than the major preglacial Beverly Valley to the west.

Much of the underlying mudstone and siltstone was exposed before glaciation and this was eroded by the Cherry Grove Glacier to provide the clay of the Bronson Lake Formation. The maximum extent of the formation in the Sand River map area is uncertain, mainly because in the southwest corner it is difficult to differentiate the Bronson Lake Formation from other glacial units. Gold (1978) believed that his lowermost till, unit 4, which correlates with the Bronson Lake Formation, does not extend beyond the Kikino Valley and that in fact the Kikino Valley represents the terminal position of the first glaciation in the area, presumably the Cherry Grove Glaciation.

However, the substantial width of the valley indicates that it was probably not confined by a glacier margin, and that it formed over a much longer period than during a short-lived glacial event. It is uncertain therefore that the terminal position of the Cherry Grove Glaciation is marked by the Kikino Valley.

Retreat phase

Proglacial lakes developed along the retreating margin during the Cherry Grove Glaciation in the Sand River map area. In a number of places within the Helina Valley lacustrine clay of the Muriel Lake Formation was deposited over the till of the Bronson Lake Formation.

The bulk of the Muriel Lake Formation, however, consists of glaciofluvial sand and gravel that were deposited during the latter phases of the Cherry Grove Glaciation. Within segments of the buried valleys, and on the upland south of the Bronson Lake Channel, these coarse deposits formed a protective mantle on the Bronson Lake till.

Elsewhere, the Bronson Lake Formation was exposed and later eroded during the following nonglacial period. In the area around Ethel Lake, the top of the formation was exposed long enough for the material to become weathered.

Event two: Fort Kent Glaciation

Advance phase

In the northeast segment of the Helina Valley widespread and thick glaciofluvial sand and gravel were deposited in contact with ice, during either the latter phases of the Cherry Grove Glaciation or the early advance phase of the Fort Kent Glaciation. These sediments lie higher than the outwash farther west along the valley and form the core of the Medley Upland.

Till of the Bonnyville Formation was deposited throughout the study area during the Fort Kent Glaciation. The abundance of quartz in the till indicates that the source of the material was possibly sandstone of the Athabasca Formation to the northeast. Stratified sediment, mainly sand and gravel, that lies between two till units in the formation, indicates that more than one advance occurred during the Fort Kent Glaciation. During the first advance glacial thrusting incorporated large masses of sediment from the underlying Lea Park and Belly River formations. In places, this displaced rock was deposited at the base of the formation as intact blocks; in other places the glacier comminuted the mudstone and siltstone to produce the clayey till of unit 1. After this first advance, the glacier margin retreated from the map area, and meltwater deposited thick sand and gravel on top of unit 1 in places above the buried Sinclair, Helina, and Beverly valleys. This was followed by a glacial readvance that extended throughout the map area, during which time the sandier till of unit 2 of the Bonnyville Formation was deposited.

Thick deposits of the Bonnyville Formation that form the ridgelike uplands in the northeastern and southwestern parts of the map area probably indicate ice-marginal positions of the Fort Kent Glaciation.

Retreat phase

During the latter phases of the Fort Kent Glaciation the surface of the Bonnyville Formation was eroded by both meltwater and the reestablished regional drainage. In the central part of the map area two rivers developed, both draining northeast along the Beaver Lowlands, and ultimately merged within the topographic low above the buried Helina Valley beneath Cold Lake (figure 29). Much of the Bonnyville Formation was eroded within the valleys. Sand and gravel of the Ethel Lake Formation were deposited as the valleys formed on the surface of the Bonnyville Formation in the central part of the map area. There is no evidence that a major river channel developed following the Fort Kent Glaciation.

The surface of the Bonnyville Formation was exposed and weathered during the nonglacial period that followed. In the eastern part of the map area the weathering zone is not well-preserved or widespread. This may indicate that in the east the formation was either not exposed for a long period, or that the surface of the formation was weathered but was eroded later. In contrast, the weathered zone is well-preserved and widespread in the west. However, the Bonnyville Formation was probably exposed to more than one weathering period in the west, and this accounts for the greater degree of weathering. This is discussed in more detail later.

Event three: Ardmore Glaciation

Advance phase

A series of proglacial lakes preceded the early phases of the Ardmore Glaciation in the map area. These lakes formed as a result of meltwater flowing off the ice and by blockage of the regional drainage to the northeast by the advancing glacier. Large areas of silt and clay of the Ethel Lake Formation were deposited in these proglacial lakes in the Beaver Lowlands and on the north-facing slope of the Reita Upland. The curved distribution of thick clay, silt, sand, and gravel of the Ethel Lake Formation, extending from the Reita Upland in the east to Lac La Biche in the west (figure 33), probably defines a margin of the Ardmore Glacier. Based on the absence of both the Ethel Lake and Marie Creek formations in the southwest, initial interpretations suggested that this curved distribution of thick sediment of the Ethel Lake Formation represents a terminal moraine that marks the southwest limit of the Ardmore Glaciation. However, as is discussed later, this is probably not true: the curved distribution of thick sediment more than likely marks only a temporary ice-margin of the Ardmore Glacier.

Within the Beaver Lowlands and, to a lesser degree within the Reita Upland, much of the underlying silt and clay of the Ethel Lake Formation were eroded during the Ardmore Glaciation. This incorporated material formed a clayey lower till, which comprises unit 1 of the Marie Creek Formation. Coarser material that was incorporated higher up in the glacier was deposited later, producing the sandy till of unit 2.

The abundance of carbonate in the Marie Creek till, as well as the north-south orientation of pebbles, indicate that in the eastern part of the map area the source of glaciation was slightly west of north, trending roughly parallel to the Devonian carbonate outcrop in northeast Alberta. Although the Marie Creek till is not recognized in the southwest corner of the Sand River area, the presence of a calcareous till in the Cooking Lake moraine west of the study area indicates that this glaciation extended west of the Sand River map area. Therefore, the absence of the Marie Creek till in the southwest probably indicates that it was eroded shortly after deposition.

The surface expression of the underlying rock topography was almost completely masked following the deposition of the Marie Creek Formation.

Retreat phase

During deglaciation, meltwater eroded a number of shallow, poorly defined channels on the surface of the Marie Creek Formation. Some, though not all, of the stratified sediment of the Sand River Formation was deposited at this time, either from glacial lakes or streams.

Except for the southwest corner of the map area, erosion during the following nonglacial period was minor and a widespread weathered zone developed on the surface of the Marie Creek Formation. The upper surface of the Marie Creek till was not leached of carbonates. In the southwest the Marie Creek Formation was eroded and the surface of the underlying Bonnyville Formation was exposed to a second weathering event.

Event four: Cold Lake Glaciation

The Cold Lake Glaciation was the final major glaciation to affect the study area, and as a result, geomorphic and surficial geologic data (Fenton and Andriashek 1983, in pocket) as well as stratigraphic data are available. These additional data allow a more detailed reconstruction of the history, beyond the simplistic advance and retreat phases of the earlier events.

Most of the sand and gravel of the Sand River Formation was deposited either by streams in valleys, or by lakes in lowlands dammed by the advancing Cold Lake Glacier. These deposits were immediately buried by the till of the Grand Centre Formation and thus remained unweathered. Locally, the weathered calcareous facies of the Marie Creek Formation was eroded by the fluvial and lacustrine processes.

Glacial flow indicators, such as fluted and thrust moraine, show that the last major glacial events in the Sand River area were the advances of three independent ice lobes: the Primrose Lobe, the Seibert Lobe and the Lac La Biche Lobe. The Primrose Lobe deposited the Hilda Lake and Reita Lake members of the Grand Centre Formation; the Seibert Lobe deposited the Kehiwin Lake Member of this formation, and the Lac La Biche Lobe deposited the Vilna Member of this formation.

These lobes are believed to have formed by the differentiation of the Late Wisconsinan Laurentide Glacier subsequent to the commencement of its retreat from the glacial maximum in southern Alberta. The Mostoos Highland north of the Sand River area may have contributed to the separation of the glacier into the southwest-flowing Primrose and the southward flowing Seibert lobes. The Lac La Biche Lobe may have originated in southwestern Saskatchewan, where the terminus of the lobe is recognized, with the ice flow gradually extending up-glacier from that area into and through the Sand River area.

Primrose Lobe advance

The events following the development of the different lobes are most conveniently discussed by considering each lobe independently.

The discussion of the history overlaps only where the lobes are confluent or where meltwater channels cross the lobes. No radiocarbon dates are available. The relative chronology is based upon the relationship of one landform to another or the geomorphic evolution of a landform (for example, the overriding and fluting of thrust moraine).

The Primrose Lobe flowed southwestward from a position east of the study area. The lobe extended southward into the Vermilion map area (Fenton and Mougeot 1984; Mougeot, in preparation), and may have crossed the Sand River map area into the Tawatinaw map area to the west. The subsequent advances of the Seibert and Lac La Biche lobes possibly eroded or reworked the sediment deposited by this lobe in the western half of the area (figures 47, 51 and 54).

The thrust terrain at the south end of Primrose Lake may have been formed during the southwestward advance of the Primrose Lobe, and then overridden; or perhaps it was formed later when the Marie Lake thrust was formed. Glaciotectonism south of Muriel and Sinking lakes (Tp 59, R6 and 7, W 4 Mer) built the fresh-appearing thrust moraine and formed the depression occupied by the lakes. Concurrently, or perhaps slightly later, deformation north of these lakes produced the depression occupied by Moose Lake and the thrust moraine that lies directly southeast of this lake and which extends southeast to Muriel and Sinking lakes. The thrust terrain directly north of these two lakes appears fresh whereas that in the Moose Lake area does not. Possibly this is because the thrust terrain near Moose Lake was created further up-glacier during the thrusting process and was subjected to glacial overriding following deformation. The band of thrust moraine in the southeastern part of the area south of Thompson Lake (NW1/4, Tp 59, R 1 and NE1/4, Tp 59, R 2) may have also been built at this time, and if so was probably continuous with the thrust moraine south of Muriel Lake.

The south trending ridge of thrust moraine directly east of the Kehiwin Channel and south of Moose Lake (Tp 60, R 7) lacks a fresh appearance. The ridge was likely produced during the period when the Primrose and Seibert lobes were in contact. The interaction of the two lobes has masked the original character of the thrust ridge.

The fresh-appearing thrust moraine in the Wolf Lake-Standish Lake area (Tp 65-69, R 7-8) was formed by the Primrose Lobe prior to the advance of the Seibert Lobe. Southwestward glacial flow indicators on the surface of the moraine show no evidence of being deflected or affected by the southward flowing Seibert Lobe.

The Primrose and Seibert lobes were contemporaneous and confluent for a period of time. In the center of the area directly east of Minnie Lake, glacial ice of the Primrose Lobe was deflected slightly southward by the presence of the Seibert Lobe, as shown by the southward curving flutes on the surface of the Reita Lake till (E1/2, Tp 61, R 8). Minor oscillations in the confluence of the two lobes resulted in an interfingering contact of the Reita Lake and Kehiwin Lake tills, the latter being deposited by the Seibert Lobe. The Primrose Lobe occupied the Beaver Lowlands prior to the arrival of the Seibert Lobe, however, preventing the latter from flowing east into the lowlands.

Seibert Lobe advance

The Seibert Lobe moved southwards through the western half of the Sand River map area and into at least the northern part of the Vermilion map area (Fenton and Mougeot 1984; Mougeot, in preparation), depositing the Kehiwin Lake Member of the Grand Centre Formation (figure 58).

Evidence of glaciotectonism associated with the advance phase of this lake is shown south of Touchwood and Spencer lakes where thrust moraine appears to have been overridden. Fresh-looking thrust moraine directly south of Saddle Lake in the southwest, (Tp 69, R 11-12) and the transverse moraine east of this, were produced by the Seibert Lobe. The lobe also formed what was likely an extensive east-west trending ridge of thrust moraine north of Whitefish Lake. All but the western portion of this ridge in Tp 62, R 13 was removed by the subsequent advance of the Lac La Biche Lobe. A northwest trending body of glaciofluvial sediment in Tp 58, R 12 and Tp 59-61, R 13 (figure 59), which is overlain by till deposited during the Lac La Biche Lobe advance, indicates that the southwestern part of the Seibert Lobe had stagnated and begun to down-melt prior to the advance of the Lac La Biche Lobe.

Only the northern part of the Seibert Lobe remained after the southeastward advance of the Lac La Biche Lobe. The continued southward flow of the Seibert Lobe to the north was blocked by the Lac La Biche Lobe, causing compression. This produced the extensive area of thrust moraine lying between Lac La Biche, the Beaver River, and the Sand River (Fenton and Andriashek 1983, in pocket). All of this moraine appears fresh with little sign of overriding. Also at this time local glaciotectonism produced a number of thrust hills and up-glacier depressions. Later, the depressions were water-filled to form Pinehurst Lake, Ironwood Lake, Frenchman Lake, Beaver Lake, and Eleanor Lake.

The last events associated with the Seibert Lobe were the deposition of an extensive area of glaciofluvial sand in the extreme northwestern part of the area (Tp 69, R 13) and the subsequent glacial overriding and thrusting of this sand by a minor readvance originating north of the study area.

Lac La Biche Lobe advance

The Lac La Biche Lobe followed the Seibert Lobe advance and deposited the Vilna Member of the Grand Centre Formation (figure 62). The advance covered much of the southwestern part of the area but the strongest component was a narrow ice stream, about 20 km wide, that extended from an area directly southwest of Lac La Biche southeastward across the Sand River map area, through the adjacent Vermilion map area and into Saskatchewan, crossing the Alberta-Saskatchewan border near Lloydminster (Fenton and Mougeot 1984; Mougeot, in preparation; Ellwood 1961; Prest 1968). The Lac La Biche advance overrode most of the western part of the area covered by the Seibert Lobe, eroding much of the underlying Kehiwin Lake Member and leaving only an area extending southeastward from about Tp 62, R 13 to Tp 58, R 11.

The ice stream created a band of fluted and thrust terrain, with fluted terrain along the eastern part of the terrain and thrust rubble moraine (Fenton and Andriashek 1983, in pocket, map units MTh and MTu) along the western margin. This complex extends southeastward from Whitefish Lake to about the southern boundary of the map area (Tp 58, R 9). The contact between the landform types is gradational, changing westward from well-developed flutes to flutes formed by overriding of the rubble moraine to rubble moraine that is only slightly streamlined, and finally to unmodified rubble moraine.

The eastern margin of the Lac La Biche Lobe was confluent with the Seibert Lobe. The flutes in the southern and central part of the area show the eastern portion of the Seibert Lobe being deflected slightly southeastward and continuing to flow southeast into the adjacent Vermilion map area. The margin of the two lobes is marked in the southern half of the map area by a band of stagnant ice moraine that is characterized by crevasse fillings that drape over, partially obscuring, some of the flutes (Fenton and Andriashek 1983, in pocket, map unit MSC).

In the southwestern corner of the map area directly east of Cache Lake (Tp 58-60, R 12), a band of transverse moraine formed, likely by southeastward-flowing Lac La Biche glacial ice that impinged on the west side of a mass of stagnant Seibert glacial ice. The moraine is composed of sediment of the Vilna Member and therefore is related to the Lac La Biche Lobe.

Sand River drainageway

The development of the Sand River drainageway and the events east and west of the Sand River can most easily be described in three separate sections. The development and evolution of the Sand River drainageway can be divided into a number of phases.

Phase 1

After the advance of the Lac La Biche Lobe, all three lobes stagnated in the vicinity of their contact and an ice-walled channel, likely subglacial, developed at or near the boundary of the Primrose and Seibert lobes. This channel, called the Sand River Channel, extended southward through R 7 and 8, and was the first major drainageway to develop during the deglaciation of the area. This channel can be divided into four segments: the northern segment is presently occupied by the Sand River. This segment of the channel was cut to a depth of as much as 80 m below the present level of the Sand River. The flow within this segment was originally englacial, or perhaps supraglacial, because meltwater cut down through a thrust ridge that had formed southwest of Wolf Lake (Tp 65, R 8). Two infilled segments of the Sand River Channel are now left as ridges standing as much as 20 m above the surrounding landscape. These segments are referred to as the Truman Segment, about 3 km long lying between the present-day Beaver and Sand rivers (Sec 7, Tp 63, R 8), and the Minnie Lake Segment, about 18 km long extending southward from the Beaver River to the northwest end of Moose Lake.

The southernmost segment of the Sand River Channel is the Kehiwin Channel. The history of this segment during the earlier phases is speculative because the channel has been eroded to Cretaceous bedrock in many places, and any earlier sedimentary record is lost. The Kehiwin Channel may have been a preexisting glacial channel that was reoccupied in Phase 1 of the Sand River drainageway.

Phase 2

A minor readvance or collapse of the channel wall directly south of the southern end of the Minnie Lake Segment (Sec 25, Tp 60, R 8) blocked the drainage. This resulted in the infilling of the Sand River Channel upstream of this dam. A major source of this sediment was probably the west segment of the Beaver River which began to develop at this time. This is based on test hole data north of the Truman Segment which shows that the fill within the Sand River Channel grades northward from sand to silt, indicating the source was to the south.

Phase 3

The Primrose Lobe margin stagnated in the area of Tp 61-62, R 7 and Tp 62-63, R 8, with the active margin retreating eastward to a position extending from the northeastern end of Moose Lake, through Stebbing Lake to the southern end of the Sand River (Sec 20, Tp 83, R 8). Down-melting of the stagnant ice allowed meltwater from the western part of the Beaver River to flow eastward, gradually depositing glaciofluvial sand over a broad area in much of Tp 62-63, R 8 and Tp 62-61, R 7, and creating a broad, high-level channel in the central part of Moose Lake. This eastward flow lowered the channel level from the higher position occupied during the earlier infilling of the Sand River drainageway and resulted in the abandonment of the Minnie Lake Segment. The direction of discharge from the Sand River north of the Truman Segment is uncertain; flow was such that the Truman Segment was abandoned but the sediment filling the channel was preserved. Meltwater flow is assumed to have been southeastward over an area that was subsequently covered and deformed by glacial ice during a readvance in Phase 4.

Phase 4

A subsequent minor local readvance of the Primrose Lobe overrode and thrust the glaciofluvial deposits west and south of Stebbing Lake creating the map units beginning with the labels sMT. The ice flow probably continued westward to the margin of the original Sand River drainageway, producing at that time the southwestward trending flutes and fluted thrust moraine north and northwest of Moose Lake (Tp 61-63, R 7-8; map units MTF, Fenton and Andriashek 1983, in pocket).

Phase 5

Flow from the Beaver and Sand rivers was disrupted by the Primrose Lobe readvance and ponded meltwater likely began flowing over the ice generally southeastward towards Moose Lake. As stagnant ice melted from the upland northwest of Moose Lake (Tp 61-62, R 7-8) meltwater eroded two areas of moraine, identified by labels ME and MEF (Fenton and Andriashek 1983, in pocket). These areas are covered by an extensive gravel lag. The first channel to have developed may have been the high-level channel originating in Sec 16, T 62, R 8 and trending southward and then eastward into the Moose Lake River valley.

North of the Truman Segment, a drainage channel was developed that eventually downcut through the ice and into the underlying thrust moraine. The orthogonal pattern in the upper portion of this channel indicates the water may have been following crevasses in the ice. Initially, flow from this channel was likely into the Moose Lake Channel. With the subsequent establishment of the eastern part of the Beaver River drainageway, flow from the Sand River Channel was diverted eastward.

As melting continued, the channel of the Moose Lake River was gradually uncovered. Only the glaciofluvial sediment in the area of Tp 61-62, R 7 was fluvially reworked to eliminate evidence of glacial overriding. Subsequent downcutting produced the broad channel now occupied by the present-day Moose Lake River and the sediment carried into Moose Lake was deposited on top of stagnant ice. Subsequent melting of this ice floor produced the hummocky to rolling topography of the fluvial sediment west of the lake. During this time, flow within the southern segment, the Kehiwin Channel, was sufficiently strong to prevent deposition of any sediment.

Events west of the Sand River drainageway

Any chronologic or geomorphic link between the Primrose and Seibert lobes was severed with the development of the Sand River drainageway, and later direct correlations are impossible. During Phase 1 of the Sand River drainageway, all of the Lac La Biche Lobe and at least the northern part of the Seibert Lobe had stagnated and begun to melt. The resulting meltwater formed many of the drainageways in the central part of the study area (Fenton and Andriashek 1983, in pocket).

Most segments of these meltwater channels trend parallel to either the flutes or to the crevasse fillings. Examples of this include: the Beaver River west of the Truman Segment (Sec 7, Tp 63, R 8); a number of streams flowing west into the Sand River (Tp 65-69, R 6-8); a stream flowing eastward towards the Minnie Lake Segment (Tp 61, R 8-10); a stream flowing into the Kehiwin Channel directly north of Kehiwin Lake (Tp 60, R 8-9); and Atimoswe Creek (Tp 58, R 8). The truncation of the flutes by some of the channel segments, together with the sharp margins of many channel segments, indicates that at least major portions of the channels were formed by superposition of superglacial or englacial channels that probably flowed initially along glacial crevasses formed in the stagnant ice. Perhaps an approximately orthogonal crevasse system existed in the ice with one series parallel to the flutes and the other system, shown today by the crevasse fillings, perpendicular to them. The hypothesis of one englacial or superglacial channel system, which was perpendicular to the flutes, being superimposed onto a subglacial system flowing parallel to the flutes is also possible but hydrologically less probable. Also, two different flow systems are less likely because there is no good evidence of draping of channel fills or of pirating and abandonment of segments of the subglacial system, as the other system was superimposed. Gravenor and Kupsch (1959) and Gravenor and others (1960) describe, however, the existence of an approximately orthogonal system of crevasse fillings and in a few places the superposition or draping of one crevasse fill over another for that part of the Lac La Biche Lobe just south of the study area in the Vermilion map area.

The last recorded events associated with the Seibert Lobe are the deposition and subsequent overriding and thrusting of an extensive area of glaciofluvial sand in the extreme northwestern part of the area north of Lac La Biche (Tp 69, R 13). Following stagnation and down-melting of this ice, the Owl River was formed.

Events east of the Sand River drainageway

At the close of Phase 5 of the Sand River drainageway, meltwater from the Sand River and the western part of the Beaver River flowed southward along the Moose Lake River and Kehiwin Channel. At this time the active margin of the Primrose Lobe was directly northeast of Moose Lake and extended eastward to perhaps south of Jessie, Charlotte, and Ernestina lakes. The thrust moraine southeast of Ernestina Lake (NW1/4, Tp 60, R 3) was formed. The position of the margin farther east is unknown.

Later a broad band of the Primrose Lobe margin stagnated. The limit of the active margin was transferred northward to a position north of the present Beaver River, extending eastward from about Stebbing Lake to Cold Lake. The stagnant ice was relatively free of debris judging by the low relief moraine present in this area today.

Superglacial or englacial meltwater formed channels in the stagnant ice mass. The first was perhaps a small, short-lived, east-northeast trending channel that originated east of Moose Lake and which is presently occupied by Muriel Creek (Tp 61, R 4). Later, another channel developed near the position of the present-day Beaver River, perhaps along the contact between the active and stagnant ice. As this channel downcut, it eventually drew off some of the meltwater from the Sand River drainageway so that today Moose Lake River flows northward into the Beaver River, rather than southward down the Kehiwin Channel.

Along the active ice margin north of the Beaver River a broad belt, about 10 km wide, of glacially compressed and thrust landforms developed, extending from about Barbara Lake (Tp 64, R 6) eastward to Cold Lake. The largest thrust mass was a hill or ridge built along the south side of Cold Lake; the steep down-glacier margin that rested against the stagnant ice forms a prominent south-facing scarp in Sec 36, Tp 62, R 1, and in the adjacent areas of Saskatchewan. Smaller thrust hills were formed including those south of Hilda, Moore, Tucker and Barbara lakes, Tp 64, R 2-6 (Fenton and Andriashek 1983, in pocket).

Thrusting along this belt likely was produced by local glacial flow, based on the east-west orientation of the thrust ridges that indicate southward flow. This orientation is unique to this area and contrasts with the southwest flow indicated by all the other thrust hills and flutes formed by the Primrose Lobe.

Subsequent to the development of the Cold Lake thrust, a glacial readvance broke through the ridges directly south of Cold Lake and travelled as far as the southern boundary of the map area. This readvance built the southwest trending ridges of thrust bedrock and Pleistocene sediment directly east of Grand Centre, Tp 61-63, R 2 (plate 5a), deposited the thrust moraine around Angling Lake, Tp 60, R 3 (plates 5b,c), and removed any thrust moraine that connected the ridge near Muriel Lake with that south of Thompson Lake (Fenton and Andriashek 1983, in pocket).

This minor readvance disrupted the Beaver River drainage and a lake formed on the stagnant ice west of the newly deposited thrust terrain. This lake probably covered the northern parts of Tp 62, R 3-5 and the southern parts of Tp 63, R 3-5 and deposited a thin cover of glaciolacustrine sediment in the area. Meltwater flow may have temporarily returned to the Sand River drainageway via the Moose Lake River. Eastward drainage was reestablished by flow over the ice as soon as the elevation of the superglacial lake exceeded that of the low ridge of thrust sediment lying south of Grand Centre. An ice-walled channel was excavated through this ridge in Sec 15-16, Tp 62, R 2. Subsequent melting of the stagnant ice allowed rapid drainage of the lake and erosion of the underlying till. This produced the eroded moraine and glaciofluvial units west of the thrust ridge in Tp 62-63, R 3-4.

Following the reestablishment of the eastern part of the Beaver River, water from the Sand River and the western segment of the Beaver River flowed eastward down this channel, and the Moose Lake and Kehiwin channels were essentially abandoned. Flow from the Beaver River continued eastward into Saskatchewan forming a delta in Glacial Meadow Lake (Christiansen and others 1975).

If the major thrusts that produced Wolf and Marie lakes and the part of Primrose Lake within Alberta had not taken place earlier, they occurred at this time. As mentioned previously, the Wolf and Marie thrusts are fresh-looking and show no sign of overriding, indicating little glacial scouring after their formation. The Primrose Lake thrust, which does show evidence of being overridden, could have been formed by the same ice advance that continued slightly southwestward to form the Marie Lake thrust moraine.

Following this, any remaining active parts of the Primrose Lobe north of the Beaver River and east of the Sand River stagnated and began to waste. In the vast area of stagnation moraine north of Marie, Tucker, and Wolf lakes, the drainage appears to have been influenced by an orthogonal system of crevasses or related planes of weakness in the glacier; almost all of the meltwater channels in this area are composed of orthogonal segments (Fenton and Andriashek 1983, in pocket; Rennie 1957).

A southwest trending river, extending from near Burnt Lake (Tp 67, R 3) through Bourque Lake and south through Tucker Lake (Tp 64, R 4), cut down through the ice and began to erode the underlying Pleistocene sediment. A channel extending from Sinclair Lake (Tp 66, R 5) to Bourque Lake may also have begun to form at this time. This channel is now partially infilled with till making the age less certain; the possibility the channel is palimpsest cannot be excluded.

The river flowed south across what is presently Tucker Lake and likely continued southwestward to discharge into the Beaver River. Following this the ice south and west of the lake melted, destroying the segment of the channel south of the north shore of Tucker Lake. Extensive glaciofluvial sand deposits (Tp 4-6, R 64) accumulated in this depression, partly burying the former channel. During this time the drainage may have been westward through Barbara Lake, Osborne River, and Manatokan Lake into the Beaver River. Subsequently drainage was eastward through Moore Lake and southeastward into the Beaver River. The channel from Marie Lake to Ethel Lake and the Beaver River also functioned at this time, as did the channels of the Medley and Martineau rivers which discharged into Cold Lake. Each of these drainageways is marked by extensive deposits of glaciofluvial material.

Postglacial events

Following glacial retreat, the study area underwent late glacial and Holocene events typical, throughout the plains of Canada, of a change from boreal to prairie conditions. Schwager and others (1981) described the climatic-vegetative history of the region based on the analysis of cores from a number of central Alberta lakes, including Moore Lake (Tp 64, R 4). Vegetation became established between 12 000 and 11 500 years B.P. and stagnant ice was likely gone by 10 000 B.P. Rapid warming occurred around 11 300 and 11 200 B.P. The climatic warming continued with a period of low water levels and drought between about 9000 and 6000 B.P. but by about 4000 B.P. the climate had become cooler and wetter with the modern vegetation and climate becoming established soon after (Schwager and others 1981).

Regional correlations

Table 12 summarizes the tentative correlations of the lithostratigraphic units in this study with those defined by previous workers in the region, primarily Gold's (1978) work in east-central Alberta, and Christiansen's (1968) work in Saskatchewan. Included in the table are the main criteria used in making the correlations. The correlations have differences in the degree of certainty, depending on the units involved. For example, the correlation of the upper till sequence in this study with the sequence proposed by Gold (1978) is generally strong. Conversely, the correlation of these units with those in Saskatchewan (Christiansen 1968) is weak.

Very tentative ages have been assigned to the stratigraphic sequence even though datable material was not found within any of the units (table 12). Weathered profiles on the surfaces of the buried tills establish that prolonged periods of time followed the deposition of the tills. The times during which deposition of the units occurred can be stated with confidence for only the youngest unit, the Grand Centre Formation; it was deposited during the last glaciation and probably is of Late Wisconsinan age.

Table 12. Proposed regional correlations and ages of lithostratigraphic units

Stratigraphic units in east-central Alberta		**Stratigraphic units in this study**	**Possible age**	**Stratigraphic units in Saskatchewan**	
Name	**Correlation criteria**	**Name**		**Name**	**Correlation criteria**
Till unit 1 (Gold 1978)	• uppermost till • lower matrix carbonate content than underlying till • less oxidized than top of underlying till	**Grand Centre Formation**	Late Wisconsinan	Battleford Formation (Christiansen 1968)	• uppermost till • soft, unconsolidated, massive to fissile • less oxidized than underlying till • low matrix carbonate content • basal boulder concentration
		Sand River Formation	Mid-Wisconsinan		
Till unit 2 (Gold 1978)	• high carbonate content in matrix and coarse sand • strongly oxidized surface • higher resistivity than above till • second till in sequence	**Marie Creek Formation**	Early Wisconsinan	Floral Formation (Christiansen 1968)	• fractured, jointed, highly oxidized surface • consolidated, difficult to drill • higher matrix carbonate content • second till in sequence
		Ethel Lake Formation	Early Wisconsinan		
Till unit 3 (Gold 1978)	• low carbonate content in matrix and coarse sand • slightly higher quartz content in coarse sand • third till in sequence	**Bonnyville Formation** Unit 2	Pre-Wisconsinan	Sutherland Group (Christiansen 1968) Upper till	• low dolomite content in matrix • oxidized surface • third till in sequence
Till unit 4 (Gold 1978)	• high clay content • low resistivity	Unit 1		Intertill deposits and lower till	• high clay content • low resistivity • confined to buried valleys
		Muriel Lake Formation	Pre-Wisconsinan		
Till unit 4 (Gold 1978)	• very low resistivity • high local bedrock content • high clay content • confined to buried valleys • lowermost till in sequence	**Bronson Lake Formation**	Pre-Wisconsinan	Sutherland Group (Christiansen 1968) Lower till	• high clay content • low matrix carbonate content • lowermost till in sequence • confined to buried valleys
		Empress Formation		Empress Group (Whitaker and Christiansen 1972)	• stratigraphic position • composition of clasts
		Unit 3	Early Quaternary		
		Unit 2	Early Quaternary to Late Tertiary		
Saskatchewan sand and gravel (Rutherford 1937, Stalker 1967)	• quartzite, chert and local bedrock clasts in gravel, salt-and-pepper sand on floors of buried preglacial valleys	Unit 1	Tertiary		

Surficial geology

This chapter explains the classification scheme used for the surficial map and describes the map units.

Classification of surficial terrain

The surficial sediment is described according to (1) genesis, (2) composition, and (3) morphology and relief. Each category is indicated on the surficial geology map (Fenton and Andriashek 1983, in pocket) by a symbol (figure 65). The use of the symbols is described in the later section on map unit notation. The genetic categories are the first level of map unit. All the other categories either subdivide or provide additional information about a particular genetic category.

Genetic categories

The surficial sediment is divided into seven major categories:

O – Organic; sediment deposited in marshes, bogs, fens, and swamps.
C – Colluvium; sediment deposited by mass wasting.
F – Fluvial; sediment deposited by streams.
E – Eolian; sediment deposited by wind.
L – Lacustrine; sediment deposited in standing freshwater bodies.
M – Moraine; sediment deposited as a result of glacial processes.
R – Bedrock; pre-Pleistocene sediment that has undergone lithogenesis to form well- to poorly-consolidated rock.

A number of these categories are subdivided using genetic modifiers (figure 65 and table 13) to provide more specific information on the genesis of the sediment (for example, stagnant ice moraine – MS), or the post-depositional history (for example, eroded moraine – ME). Each of these categories is described in more detail in the section "Unit Description." The term "undivided" (U) is used either to denote a genetic category that lacks the characterizing features necessary to subdivide it, or to denote a composite unit containing three or more subdivisions inseparable at the map scale.

Composition categories

These categories indicate the dominant grain size of the sediment (silt and clay for example) and for some of the moraine units the presence of significant quantities of recognizable blocks of preexisting sediment (sandstone for example, table 13). In general a unit contains more than 25% of the category indicated. When no category is indicated the composition is uncertain due to the lack of data. The one exception is the moraine units. These units are assumed to be composed of till, unless the presence of a composition symbol indicates another type of sediment.

Morphology and relief categories

Relief categories refer to the average difference in elevation between the hill, or ridges, and the adjacent depressions within a particular map unit. The categories used are: high (greater than 10 m), medium (3 to 10 m), low (less than 3 m), and flat (less than 1 m). Morphology refers to both the shape of the landforms making up the map unit and the continuity of a particular genetic category within a map unit (table 13), and includes the following types:

d – discontinuous; this term indicates a genetic category that is absent within part of the map unit, for example discontinuous lacustrine sediment (Ld). The topographic expression is controlled by the underlying unit.
dr – draped; a cover of sediment that is more than 2 m thick but which does not completely mask the underlying topography.
h – hummocky; terrain consisting predominantly of equidimensional hills and hollows.
k – knobs; one or more isolated hills generally surrounded by flat terrain.
m – rolling; terrain consisting predominantly of elongate hills and hollows with a length-to-width ratio of generally more than two. Hills and hollows vary from parallel to nonoriented.
p – pitted; relatively flat terrain with prominent depressions or pits.
r – ridge(s); one or more parallel to subparallel, elongate landforms with a length-to-width ratio of more than two. Ridges generally rest on a level surface but may, in a few places, have associated depressions or hollows.
t – terrace; an essentially level surface bounded by an ascending and/or a descending scarp. The

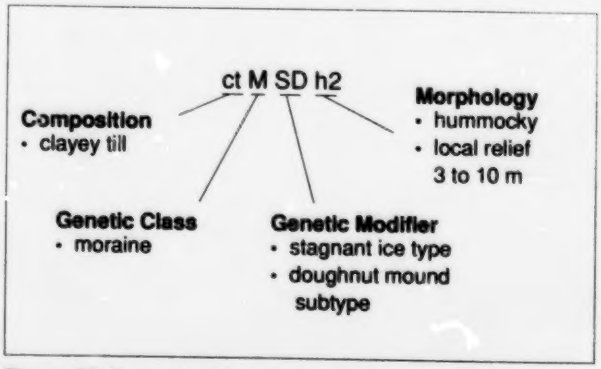


Figure 65. Example of the map unit notation used on surficial geology map.

Table 13. Symbols used on surficial geology map.

Unit Notation

Composition

a – sand, silt, and clay
b – sand and silt
c – clay
f – fine-grained: silt and clay
g – gravel and sand
$ – silt
s – sand
t – till
r – rock: undivided; one or more of shale, siltstone, and/or sandstone
sh – shale
ss – sandstone
m – mixed: three or more of the above components. Each component >10 percent of the unit.
If blank: composition is uncertain or for moraine units is till.

Genetic Class

O – Organic
C – Colluvium
F – Fluvial
E – Eolian
L – Lacustrine
M – Moraine
B – Bedrock

Genetic Modifier

CD – eroded slope
CS – slumped colluvium
D – dissected
E – eroded
F – fluted
G – glacial
IC – ice-contact
N – transverse
S – stagnant ice
SC – crevasse filling
SD – doughnut mound
SI – irregular
T – thrust
W – washboard
Δ – delta
u – undivided: implies either unit is without the characterizing features to subdivide it or the unit is a composite containing three or more subdivisions inseparable at this map scale.

Morphology and Relief

d – discontinuous; unit absent in some places
dr – drape: unit more than 2 m thick but does not completely mask underlying topography
f – flat: local relief less than 1 m
h – hummocky: assemblages of hills and hollows; approximately equidimensional
k – knob(s): one or more isolated hills on a generally level surface
m – rolling: alternating concave and convex morphologic elements with a length to width ratio of more than 2; elements parallel to nonoriented
p – pitted: a relatively flat area having prominent depressions or pits
r – ridge(s): one or more convex, parallel to sub-parallel, morphologic elements with a length to width ratio of more than 2; may rest on a level surface or have associated hollows
t – terrace
v – veneer: less than 2 m thick
1 – low local relief, less than 3 m
2 – moderate local relief, 3 m to 10 m
3 – high local relief, more than 10 m

symbol may indicate multiple terraces where they cannot be separated at the map scale.

v – veneer; this term indicates that the sediment forming the particular genetic category is less than 2 m thick within the map unit. The topographic expression is derived mainly from the underlying unit.

Map unit notation

A combination of letters and numbers is used to designate each map unit, for example ctMSDh2. The lowercase letters (where present) preceding the capital letters indicate the composition of the unit. The first uppercase letter indicates the genetic class. The following uppercase letter(s) indicate the genetic modifier and provide additional information about the genetic unit. The lowercase letters following the uppercase letters indicate the morphology, the type and the amount of local relief, and whether the genetic class is discontinuous within the map unit (figure 65 and table 13).

The absence of the compositional, genetic, and/or morphologic modifier for a particular unit indicates the data are insufficient to determine that information. The map units generally show the sediment to be expected in the upper 3 m. The exception is in areas where one moraine type overlies another; here the upper moraine may be up to 7 m thick.

Unit proportion is indicated by symbols; for example O//F indicates that 25%± about 10% of the surface is organic sediment, and 75%± about 10% is fluvial sediment. The genetic symbol to the left of the double slash (//) also indicates that this sediment likely overlies the sediment indicated by the symbol on the right (F in the example) in at least part of the map unit. Units in which the relative proportions of two genetic categories cannot be estimated are shown by a plus sign (+) between the categories, for example O+F.

Examples of Map Unit Notation

(1) ctMSDh2 Moraine (map symbol M), forming doughnut type stagnant ice terrain (SD), composed of clayey till (ct) with a hummocky topography (h) of moderate relief (2).

(2) $\frac{\text{Ldr}}{\text{sstMThm23}}$ Lacustrine sediment (L) of unknown composition draped (dr) over hummocky (h) to rolling (m) thrust moraine (MT) of moderate to high relief (23) and composed of till (t) with recognizable sandstone masses(ss).

(3) $\frac{\text{gFGh1+O}}{\text{MSh2}}$ Hummocky (h) low relief (1) glaciofluvial (FG) gravel and sand (g) plus organic sediment (O); relative proportions unknown; one or both likely discontinuous; both overlie hummocky (h) moderate relief (2) stagnant ice moraine (MS) composed of till.

(4) sLf MSh1 MT	Flat (f) lacustrine (L) sand (s), overlying hummocky (h) low relief (1) stagnant ice moraine (MS) composed of till overlying thrust moraine (MT) in which the topography cannot be determined. In general all three will be found in the upper 3 m over part of the unit but locally there will be areas of thick MS where the MT will be below 3 m.
(5) Ov sFG//MTh1	Organic veneer (Ov) overlying a unit composed of about 25% glaciofluvial (FG) sand (s) of unknown morphology and about 75% hummocky (h) low relief (1) thrust moraine (MT).
(6)MSDDm3	Moraine (M) composed of doughnut type stagnant ice terrain (SD) that has been dissected (D) by a number of channels to form a rolling (m) high relief (3) topography. Moraine composition is likely till.

Unit description

This description is organized in the same order as shown on the legend for the surficial map (Fenton and Andriashek 1983, in pocket). The unit descriptions are to the level of either genetic class or genetic class plus genetic modifier (table 13). There are not two descriptions for a genetic unit with two different compositional or morphologic subdivisions.

Recent deposits

O – Organic deposits; this unit includes bog, fen, marsh and swamp deposits that have accumulated in low areas on the land surface. The sediment consists of woody to fibrous to mucky peat. This unit commonly includes near its base one or more of lacustrine silt, clay, sand, gravel, or marl. In some places however, the organic sediment rests directly on till, or eolian or fluvial sand. This unit covers a major part of the land surface in the northern half of the map area but is a minor component in the south. Organic sediment is found mainly in abandoned meltwater channels and depressions in thrust moraine and stagnant ice moraine. Larger deposits are generally over 2 m thick, and one bog examined in the northeastern (Tp 69, R 5) part of the area is more than 5 m thick with a metre of marl near the base.

C – Colluvial deposits undivided; this unit includes sediments that have reached their position by gravity-induced movement. The sediment is unstratified to moderately well-stratified, nonsorted to poorly sorted, and includes clay to boulder-size material. The morphology is hummocky to rolling, and relief is generally low to flat. This unit is confined primarily to the sides and floors of valleys such as the Sand River and Beaver River. The unit is thinnest in the upper part of the slope and thickest in the valley floors. Along the sides of the Kehiwin Channel (Tp 59, R 7) the colluvium is locally more than 7 m thick. The unit is poorly suited for construction because the sediment may still be undergoing movement and may have a high potential for failure.

Small areas of unmapped colluvium are present in some of the low areas in the hummocky to rolling moraine. In general, the higher the relief the greater the chances are of colluvium being present and the greater its probable thickness. Where the map scale and data permit, this unit is divided into eroded slopes (symbol CE) and slump deposits (CS); otherwise both units CE and CS are included under the term C.

CE – Eroded slope deposits; this unit lies along valley sides that have undergone erosion, usually by creep, leaving in place a thin or discontinuous cover of colluvium. The morphology is hummocky with low to flat relief. The unit is thin or absent near the top of the slope but may thicken to more than 2 m near the base.

CS – Slump deposits; this unit consists of colluvium deposited by slumping, usually as rotational faults, in which slump scars are still visible. The morphology is rolling to hummocky with low to moderate relief. This unit is present in some areas of the Kehiwin Channel, the Beaver River valley and north of Touchwood Lake (Tp 67, R 10). The unit is unsuitable for construction because sediment may fail in or adjacent to the unit.

E – Eolian deposits; this unit includes all wind-deposited sediment including both traction and suspended-load material. The sediment is generally medium to fine, well-sorted sand; in some places the unit includes silt. Where exposed, the sand typically appears unstratified but locally large- and small-scale cross-bedding may be visible. The morphology is generally hummocky and the relief moderate to flat.

Eolian deposits are found in or adjacent to fluvial deposits and have a minor areal extent. The deposits generally form a discontinuous succession of dunes and are mapped as a separate unit in only a few areas (Tp 61, R 8, and Tp 67, R 8). This unit could provide a good source of clean, well-sorted sand.

F – Fluvial sediment, undivided; this unit includes material deposited by modern rivers and streams: sand, silt, and small amounts of gravel and organic matter. The sediment is commonly moderately well to well-sorted with well-developed to obscure stratification. The morphology is generally flat to rolling with low relief. A particular unit may include two or more terraces. Thickness is variable and may exceed 3 m in places. The unit is present on floors of modern stream and river valleys such as the Beaver River and Sand River, Reita Creek (Tp 61, R 2), Jackfish Creek (Tp 64, R 4), Owl River (Tp 69, R 13), and Amisk River (Tp 63, R 13). This unit is generally a poor source of aggregate because of the presence of clay and organic sediment.

FΔ – Deltaic deposits; the unit includes sediment deposited at the mouth of modern streams and rivers. The sediment and morphology are similar to undivided fluvial deposits. This unit is present at the mouth of the Medley River (Tp 65, R 1) and Owl River (Tp 68, R 13).

FE – Fluvial and eolian deposits, undivided; both types of sediment are present in this unit but cannot be separated at the map scale. The unit generally is composed of sand with small amounts of silt. The morphology is commonly hummocky with low to flat relief.

FL – Fluvial and lacustrine sediment, undivided; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The unit is generally composed of sand, silt, and a small amount of clay. Morphology is flat to rolling with low relief.

FU – Fluvial deposits, undivided; this unit includes Recent and Pleistocene age deposits that are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment is generally sand and silt with a small amount of gravel, clay and organic matter. The morphology is rolling to hummocky with low to flat relief. The unit is a poor to good source of aggregate depending on the proportion of silt, clay, and organic matter. The better quality material generally is derived from glaciofluvial sediment included in this unit.

L – Recent lacustrine deposits, undivided; this unit includes sediment deposited in and adjacent to present-day lakes. The sediment includes offshore sand, silt, clay, and organic matter, and nearshore or onshore sand and gravel. The sediment is generally well-sorted and well-stratified. The morphology is commonly rolling with low to flat relief. The beaches may include ridges up to 1.5 m high. Lakes over 5 km^2 in area usually have boulder or cobble beaches and nearshore lag deposits along that part of their shore exposed to strong wave action. This coarse sediment is derived mainly from erosion of till along the shoreline. The larger lakes also show the effect of wind-driven ice in the form of ice ramparts and local gouging of the shoreline. The shore of Cold Lake, particularly the eastern part, contains many examples of this.

Shoreward of the lake margins, the lacustrine deposits are generally thin and of limited areal extent, having been deposited only during atypically high lake levels.

This unit may be suitable as a construction site if the relief is low and the site is high enough above the water table.

LU – Lacustrine deposits, undivided; this unit includes deposits of Recent and Pleistocene age lacustrine sediment inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment is commonly fine sand and silt. The morphology is rolling with low to flat relief.

Pleistocene deposits

FG – Glaciofluvial deposits, undivided; this unit consists of fluvial sediment deposited by glacial meltwater. The material is predominantly sand and gravelly sand with a small proportion of gravel and silt. Visible structure ranges from unstratified (especially in the units composed only of sand) to stratified and the sediment is moderately well to well-sorted. The morphology ranges from flat to rolling to hummocky to pitted. The relief is generally low but locally may be moderate. This unit is found mainly in the central, east-central, and northeastern parts of the map area (Fenton and Andriashek 1983, in pocket). The sediment thickness ranges from a thin discontinuous cover to more than 4 m. Glaciofluvial sediment can provide a good source of high quality aggregate if the deposit is large and clean. See additional comments in the section on economic geology.

FGΔ – Glaciofluvial delta deposit; this unit consists of sediment deposited as meltwater empties into a glacial lake. The composition and morphology are similar to those of the undivided glaciofluvial unit (FG) above. Coarser sediment may generally be found in the upstream part of the delta. Examples of this unit are found on the north side of Tucker Lake (Tp 64, R 5); in the northwest corner of Tp 67, R 4; and south of Moore Lake (Tp 63, R 4).

FGIC – Ice-contact glaciofluvial deposits; this unit consists of sediment deposited on the land surface by meltwater in contact with glacial ice. The material is mainly sand and gravelly sand with local silt, clay, or till. The sorting is good to poor and structure differs from unstratified, to poorly stratified to well-stratified. Bedding may show faulting or folding caused by collapse as the supporting ice melts. The morphology is generally hummocky to rolling with low relief. This unit is of small areal extent and is found mainly west of Moose Lake and south of Beaver River (Tp 58-60, R 8-9). The thickness is generally less than 2 m. Deposits of this unit may be suitable as a local aggregate source but are generally small with numerous and abrupt lateral changes in sediment grain size and quality. If present, large masses of till may make excavation of aggregate difficult.

FLG – Glaciofluvial and glaciolacustrine deposits, undivided; terrain in which the two units are inseparable due to a similar appearance, or to the small size of the areas covered by the individual units. The material is typically well-sorted sand and silt with a small proportion of clay or gravel, or both. The structure ranges from unstratified to stratified. The morphology is flat to rolling with low relief. Major deposits of this unit are found southwest of Tucker Lake (Tp 64, R 5) extending eastward to Cold Lake (Tp 64, R 2; Fenton and Andriashek 1983, in pocket). The sediment is generally more than 2 m thick and is known from test hole data to exceed more than 5 m in some places.

FGSI – Stagnant-ice glaciofluvial deposits; this unit consists of glaciofluvial sediment with a topography characteristic of deposition on melting and collapsing stagnant ice. The material is typically sand with local gravel or silt. The structure is unbedded to bedded and locally the sediment may show evidence of collapse such as folding or faulting. The morphology is hummocky with low to moderate relief. This unit is of minor areal extent and is generally more than 2 m thick. The deposits may have abrupt changes in grain size and are suitable only for local sources of moderate quality aggregate.

LG – Glaciolacustrine deposits, undivided; this unit includes sediment transported by meltwater and deposited in glacial lakes. The sediment is mainly offshore sand and silt and a small amount of gravel and clay. Nearshore and onshore sand and gravel are minor components. The deposits are generally well-sorted and stratified. The morphology is flat to rolling with low relief. This unit is of minor areal extent and is found mainly west of Edward Lake (Tp 63, R 5), west of Barbara Lake (Tp 64, R 6 and 7), and northeast of Ardmore (Tp 62, R 3). The thickness is generally greater than 2 m and test holes show that the thickness locally exceeds 3 m. The flat morphology of this unit makes it attractive for construction sites but the unit occupies low areas and has high potential for groundwater and frost heave problems.

LGSI - Stagnant ice glaciolacustrine deposits; this unit includes glaciolacustrine sediment with a topography characteristic of deposition on melting and collapsing stagnant ice. The sediment consists of silt with a small amount of sand and clay. The structure is unstratified to stratified and strata may show faulting or folding resulting from collapse associated with melting ice. The morphology is hummocky with low to moderate relief. The unit is of minor areal extent and is best observed west of Edward Lake (Tp 63, R 5, unit fLGSIh1; Fenton and Andriashek 1983, in pocket). The thickness locally exceeds 3 m.

M – Moraine; moraine has been defined in a number of ways by different authors. The following paragraphs describe how the term is being used here.

Moraine is the terrain consisting of the sediment deposited by glacial processes. The sediment is mainly till (a heterogeneous mixture of sand, silt, clay, and a small amount of pebbles, cobbles, and boulders). However, locally this unit either includes discontinuous layers of stratified sediment, generally sand, or is composed predominantly of one or more of mudstone, siltstone, and sandstone or preexisting till or stratified drift. The morphology ranges from hummocky to rolling, and the relief from high to flat. A more detailed description is found in the following sections describing the subdivisions of moraine.

The moraine unit, as defined here, extends from the surface to the base of the sediment deposited by the glacial advance that formed the moraine. Moraine thickness can be up to 150 m in some glacial thrust landforms (map unit MT, Fenton and Andriashek 1983, in pocket) although generally moraine is less than 10 m thick. The chapter describing the Grand Centre Formation contains additional information on this unit.

Moraine is the major terrain unit, covering about three-quarters of the map area. The moraine has been divided into a number of units; those of major areal significance are: fluted moraine (unit MF, Fenton and Andriashek 1983, in pocket) covering about 10% of the area; stagnant ice moraine (unit MS) covering about 20% of the area; thrust moraine (unit MT) covering about 30% of the area; and undifferentiated moraine (unit MU) covering about 7% of the area.

Almost all of the moraine types are composed of sediment of the Grand Centre Formation (table 2) which consists dominantly of till, with some displaced Cretaceous sediments in the thrust moraine areas. The Grand Centre Formation is subdivided into four members mainly on the basis of till grain size. Additional comments on the properties and composition of the moraine can be found in the section describing the Grand Centre Formation. Comments on the suitability of moraine units for construction can be found in the section on economic geology.

MD – Dissected moraine; terrain dissected by many closely spaced meltwater channels (plate 7). Eroded and uneroded parts of the landscape cannot be separated at the map scale. The sediment consists of till with a small amount of sand and gravel. The morphology is generally rolling to hummocky with low to moderate relief. The morphology ranges from isolated hills and ridges to a generally level surface that has been eroded but which still

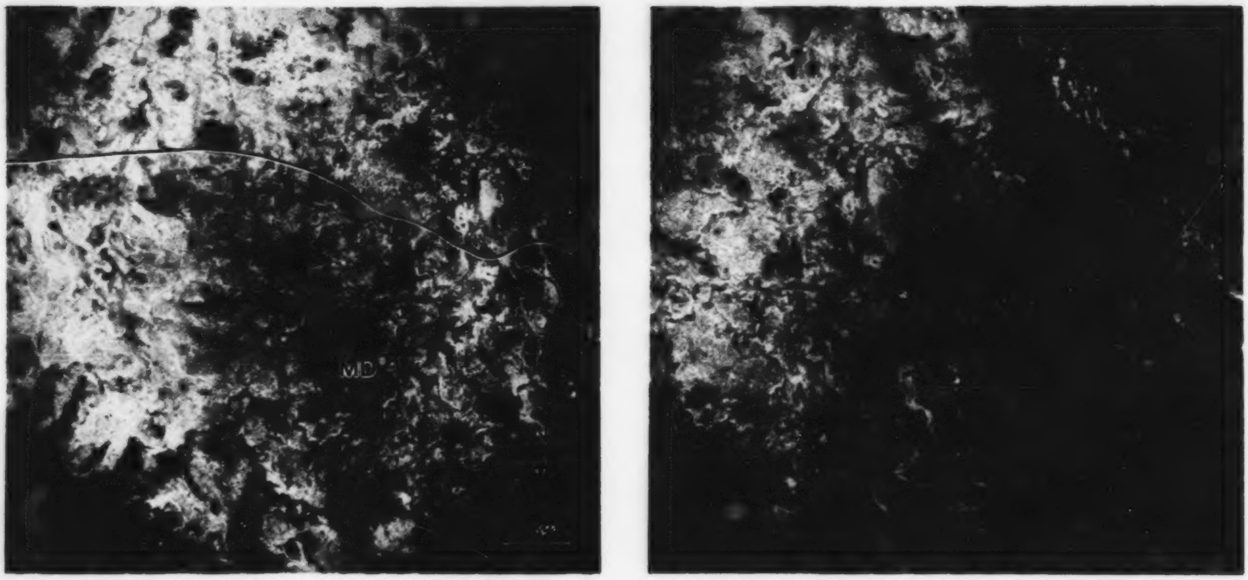


Plate 7. Dissected moraine, map unit MD. Stereo aerial photographs showing terrain dissected by many closely spaced meltwater channels such that the eroded and uneroded land cannot be separated at this map scale (SE 1/4, Tp 69, R 9). Alberta Government photos: AS112-5416, numbers 13 and 14.

retains part of its original character and elevation. The unit is of minor areal significance.

MDU – Dissected moraine and undivided moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment consists of till and a small amount of sand and gravel. The morphology is hummocky with moderate to low relief. The unit is of minor areal significance.

ME – Eroded moraine; terrain in which the moraine has been partly eroded to form a relatively level surface with none of the original surface remaining (plate 8). The sediment consists of till with locally a thin sand and gravel lag. The morphology is hummocky to rolling with low relief. This unit also includes erosional terraces along the Beaver River.

MEF – Eroded moraine and fluted moraine complex; terrain in which the two map units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment consists of till with local thin sand and gravel lag. The morphology is rolling to ridged with low to moderate relief. The unit is of minor areal significance.

MEU – Eroded moraine and undivided moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment consists of till with local thin sand and gravel lag. The morphology is rolling to ridged with low to moderate relief. The unit is of minor areal significance.

MF – Fluted moraine; this unit includes all glacially streamlined terrain. The morphology is rolling to ridged, to hummocky in some small areas, with low to moderate relief. The landform ranges from alternating furrows and ridges to nearly equidimensional smoothed hills; all are parallel to the direction of glacial flow. The sediment is generally till and locally may include some incorporated preexisting Pleistocene sediment, and sand of possibly pre-Pleistocene age. The thickness is generally more than 3 m. Fluted terrain covers about 10% of the surface and includes: a major southeastward trending belt south of Lac La Biche (Tp 65, R 13; and plate 9), two southwest trending areas west and south of Cold Lake and southwest of Primrose Lake, and smaller areas near Touchwood Lake (Tp 68, R 10), Seibert Lake (Tp 66, R 9), and northwest and northeast of Moose Lake (Tp 61, R 6-7).

Fluted moraine is generally composed of till making the ridges well-suited for fill or as a construction site. Low areas between ridges may be wet or locally contain wetlands such as fens or marshes. In moderate relief areas the rolling nature of the terrain can make cultivation difficult.

MFU – Fluted moraine and undivided moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment consists mainly of till. The morphology is

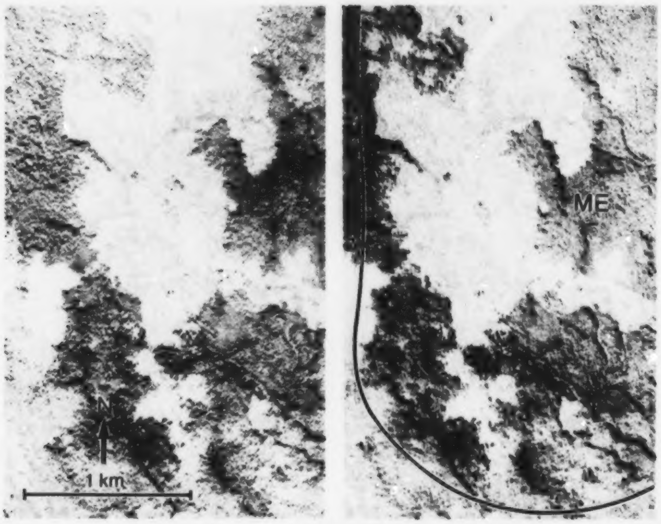


Plate 8. Eroded moraine, west of Touchwood Lake (Sec 1, Tp 68, R 10), map unit ME. Stereo aerial photographs showing terrain in which the moraine has been eroded to a relatively low surface with none of the original surface remaining. Alberta Government photos: AS114-5414, numbers 90 and 91.

rolling to hummocky with moderate to low relief. The unit is of minor areal significance, for example west of Kehiwin Creek (Tp 59, R 7).

MN – Transverse moraine; this terrain consists of parallel to subparallel, discontinuous ridges and, in some small areas, hills that are perpendicular to the local glacial flow direction. The sediment is mainly till with lenses of sand or gravel in places. The morphology is generally ridged to rolling and in small areas, hummocky. Relief is moderate to high. The sediment is generally more than 3 m thick. This unit forms a significant part of the terrain in the southwest: a north-south trending band west of Saddle Lake (Tp 58, R 12) and an east-west trending band east of Saddle Lake.

Transverse moraine is similar in appearance to thrust moraine but it is inferred that the genesis of transverse moraine likely does not involve the glaciotectonic processes that act to produce thrust moraine.

MNU – Transverse moraine and undivided moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The unit generally consists entirely of till. The morphology is hummocky to rolling with low to moderate relief and the thickness is more than 3 m. This unit is of minor areal significance, present mainly east of Saddle Lake (Tp 58, R 11).

MS – Stagnant-ice moraine, undivided; this terrain was likely formed by the lateral movement of super-glacial sediment as it collapsed in response to the melting of buried ice. This map unit is classed as undivided because it either has no obvious features to place it in one of the subdivisions of stagnant-ice moraine described below, or because it is a complex of two or more types of stagnant-ice moraine that are inseparable at the map scale used. The moraine is composed mainly of till and locally includes sand, silt, clay, or gravel of glaciofluvial or glaciolacustrine origin. The morphology is hummocky with low to high relief. In general the slope angle increases with relief. The relief of the individual hummocks in the landscape is the end product of both the fluidity of the sediment during melting and the initial thickness of sediment in the glacial ice. The fluidity is a function of the amount of water in the sediment at the time of deposition. In turn, the water content is controlled by the rate of melting, the rate of drainage, which is influenced by the texture of the sediment (sandy sediment drains more rapidly), and the thickness of the supraglacial debris (thicker debris insulates the ice thereby decreasing the rate of melting) (Clayton 1967; Clayton and others 1980).

The thickness of the unit differs from place to place, although in general it is more than 3 m thick. In small areas of low relief the thickness is less than 3 m. Stagnant-ice moraine, including all of its subdivisions, is a major terrain unit forming about 20% of the area. Undivided stagnant-ice moraine (MS) is a minor unit, present in only a few small areas. All types of stagnant-ice moraine may contain small deposits of poor to moderate quality aggregate. The moderate and high relief components of the terrain can present problems during construction or cultivation.

Stagnant-ice moraine has been divided into a number of units on the basis of morphology and

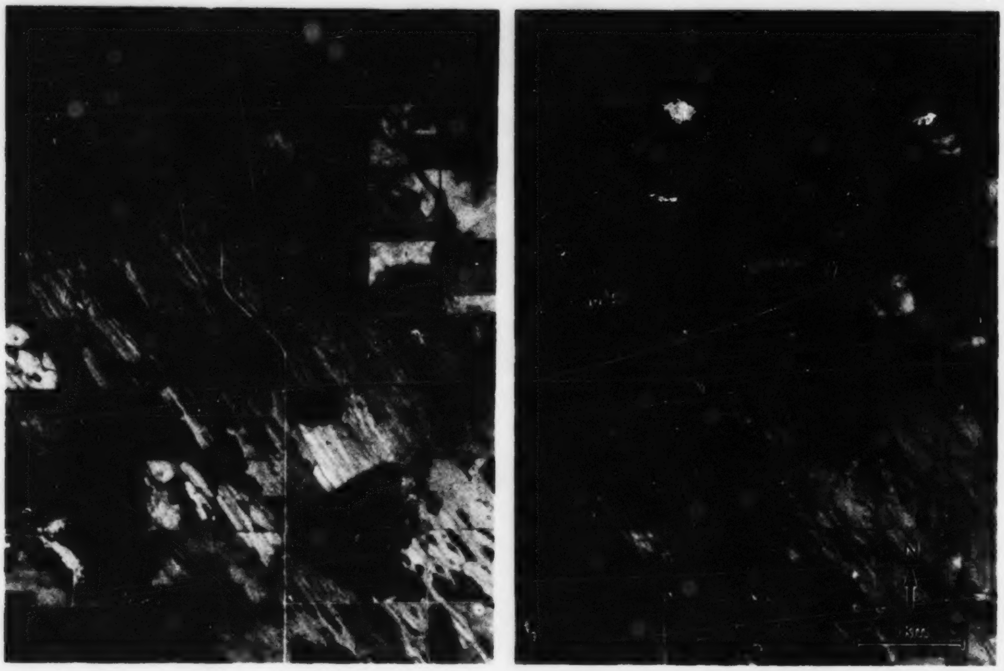


Plate 9. Stereo aerial photographs showing fluted moraine (map unit MF) and crevasse fillings (indicated by the two arrows), southeast of Vincent Lake (NW 1/4, Tp 58, R 9). Crevasse fillings or linear disintegration ridges are stagnant ice moraine consisting mainly of subparallel to intersecting ridges believed to have been formed by the filling of crevasses in the ice with glacial debris. Alberta Government photos: AS1111, line 39, numbers 34 and 35.

photo pattern. These are crevasse fillings (MSC), doughnut moraine (MSD), irregular moraine (MSI), and undivided stagnant-ice moraine (MS) which has been described above.

MSC – Crevasse fillings or linear-disintegration ridges; stagnant-ice moraine consists mainly of subparallel (plate 9) to intersecting ridges believed to have been formed by the infilling, with glacial debris, of crevasses in the ice (Gravenor and Kupsch 1959; Gravenor and others 1960). The sediment consists of till with a small amount of stratified glaciofluvial sediment locally. The morphology is ridged to rolling with low to moderate relief. Thickness is generally more than 2 m. The crevasse fillings are present mainly in a southeast trending band originating east of Vincent Lake (Tp 59, R 9, Fenton and Andriashek 1983, in pocket). Sediment in this terrain is mainly till, making the crevasse fillings poor prospects for aggregate.

MSD – Doughnut moraine; stagnant-ice moraine consists of hummocks with a central depression that gives each a doughnut-like appearance (plate 10). The central depression likely formed during the last stage of ice stagnation by the melting of a remnant of glacial ice inside the base of the hummock (Clayton 1967). The sediment is mainly till although locally small amounts of glaciolacustrine or glaciofluvial sand, silt, clay, or gravel may be present. The morphology of the unit is hummocky with low to moderate relief. The sediment is generally more than 3 m thick. This unit covers a considerable part of the northeastern, east-central, and southeastern corners of the map area (Fenton and Andriashek 1983, in pocket). Some hummocks may contain sufficient sand and gravel to provide local sources of poor to moderate quality aggregate.

MSI – Irregular moraine; stagnant-ice moraine consisting of irregularly-shaped hummocks (plate 11). The unit may include small areas of doughnut-type hummocks in some places. The hummocks consist mainly of till and may contain small amounts of sand, silt, clay, or gravel deposited in a glaciolacustrine or glaciofluvial environment. The morphology is hummocky with low to high relief. The thickness is variable but is generally more than 3 m. This unit forms a considerable part of the terrain in the northeast and smaller areas are present in the southeast and southwest.

Sand and gravel deposits within the unit are commonly small and of moderate to poor quality.

MSCD – Crevasse fillings and doughnut moraine complex; terrain in which the two units are inseparable due to the small size of the areas covered by the individual units. The sediment consists mainly of till with a small amount of sand, silt, clay, or gravel, in some places. The morphology is

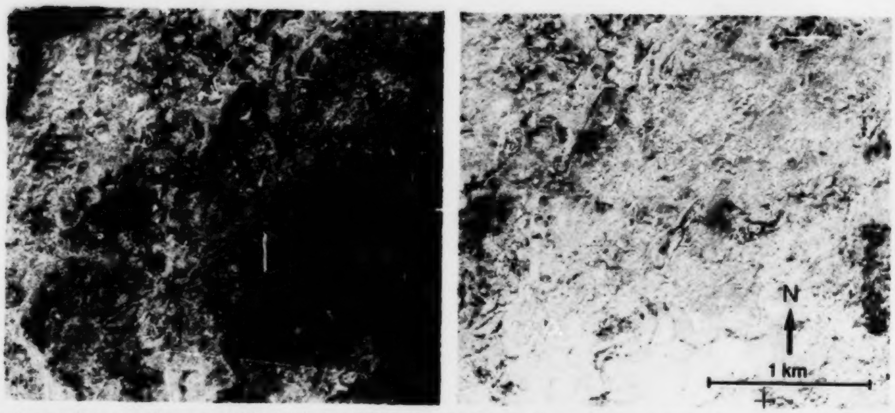


Plate 10. Doughnut moraine, southeast of Muriel Lake (SW 1/4, Tp 59, R 4), map unit MSD. Stereo aerial photographs showing stagnant ice terrain consisting of hummocks with a central depression which gives each a doughnut-like appearance. Alberta Government photos: AS125-5402, numbers 15 and 16.

generally hummocky with low to moderate relief. This complex is of minor areal significance.

MSCI – Crevasse fillings and irregular moraine complex; terrain in which the two units are inseparable due to the small size of the areas covered by the individual units. The sediment is composed of till with locally small amounts of sand, silt, clay, or gravel. The morphology is generally hummocky with low to high relief. This complex is of minor areal significance. Thickness is generally more than 3 m.

MSDI – Doughnut and irregular moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment is composed mainly of till. The morphology is hummocky with low to high relief. This complex is found primarily in the southeast. The thickness is generally more than 3 m.

MSDU – Doughnut moraine and undivided moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment is composed mainly of till. The morphology is hummocky, with low to high relief. This complex is of minor areal significance. The thickness is generally more than 3 m.

MSF – Stagnant-ice moraine and fluted moraine complex; terrain in which the two units are inseparable due to the small size of the areas covered by the individual units. The sediment is composed mainly of till. The morphology is hummocky to rolling with low to moderate relief. The thickness is generally more than 3 m. This complex is of minor areal significance.

MSN – Stagnant-ice moraine and transverse moraine complex; the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment is composed mainly of till with local sand lenses or stringers. The morphology is hummocky to rolling with moderate to low relief. The thickness differs but is generally more than 3 m. This complex is of minor areal significance.

MSU – Stagnant-ice moraine and undivided moraine complex; terrain in which the two units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The sediment is composed mainly of till with local sand lenses or stringers. The morphology is hummocky to rolling with moderate to low relief. The thickness varies but is generally more than 3 m. This complex is of minor areal significance.

MT – Thrust moraine; this unit consists of masses of originally subglacial sediment incorporated, transported, and deposited by a glacier, more or less intact. The moraine is composed of two or more of: syngenetic till, preexisting Pleistocene sediment, unconsolidated Tertiary sediment, Cretaceous sedimentary rock.

Thrust moraine map units consist of either isolated hills forming an individual thrust mass generally less than 10 km^2 in area, or a series of elongate hills that extend laterally for many kilometres and are perpendicular to the local glacial flow direction. Examples of the latter are the extensive thrust moraine in the Fork Lake, Lac La Biche, and Touchwood Lake areas. Individual thrust masses generally consist of an elongate to equidimensional hill that is composed of a series of smaller arcuate hills perpendicular to the local glacial flow direction. Individual features may be situated directly down-glacier of a depression that is commonly filled with water to form a lake, for

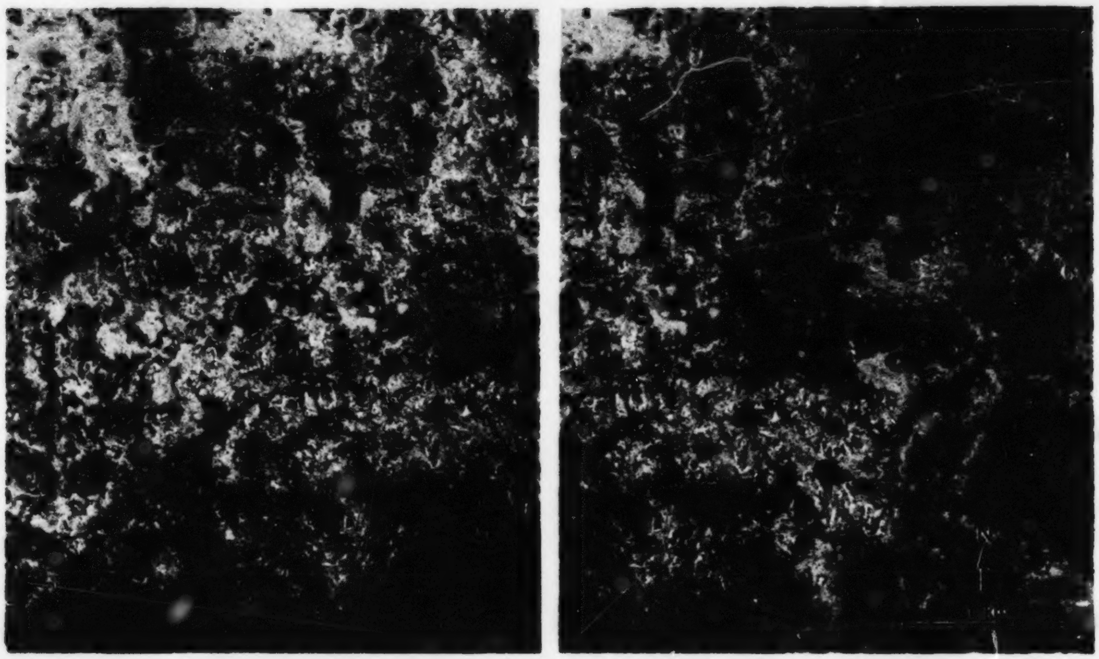


Plate 11. Irregular moraine (SE 1/4, Tp 69, R 5), map unit MSI. Stereo aerial photographs showing stagnant ice terrain consisting mainly of irregularly shaped hummocks. Alberta Government photos: AS112-5500, numbers 225 and 226.

example Marie Lake (Tp 65, R 3), Wolf Lake (Tp 65, R 7), and Pinehurst Lake (Tp 65, R 10). This unit is more than 3 m thick and is known to exceed 100 m in thickness in some thrust areas.

The thrust moraine unit forms a major part of the area, for example south of Wolf Lake, Moose Lake (Tp 60, R 7), Muriel Lake (Tp 59, R 5), Cold Lake (Tp 63, R 1), Thompson Lake (Tp 59, R 2), and in the northwest quarter of the map area. The variety of material incorporated into this terrain results in abrupt lateral and vertical changes in sediment type. Also, glacially induced deformation during the excavation and deposition of the sediment has resulted in material that is likely both crushed and weakened by a number of shear planes. The sediment can be expected to have a lower soil strength and be more prone to failure compared to the material composing the other moraine types. Therefore, excavations in this unit may have a greater tendency to fail, particularly if the cut is oriented perpendicular to the direction of thrusting.

Although thrust moraine is recognized throughout the glaciated part of the Central Plains of North America, in the Sand River area this unit includes a variety of landforms, some of which have not been described before. Consequently, this unit has been singled out for a more detailed description (see following section on glaciotectonic features).

MTF – Fluted-thrust moraine; terrain composed of thrust material that was subsequently fluted, probably by the same glacial advance. The composition is similar to that of thrust moraine. The morphology is rolling to ridged with moderate to high relief. The unit forms a large part of the terrain in the northwest (Tp 68, R 13 and Tp 63, R 11), the north-central (Tp 67, R 8), northeast (Tp 68, R 3 and Tp 66, R 1-2), and southeast (Tp 60-58, R 2-4) regions of the map area.

MTE – Thrust moraine and eroded moraine complex; terrain in which the units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The composition is similar to that of thrust moraine with a thin, discontinuous cover of sand or gravel in the eroded areas. The morphology is hummocky with low to high relief. The thickness varies but is generally more than 3 m. This complex forms only a small part of the area.

MTN – Thrust moraine and transverse moraine complex; terrain in which the units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The composition is similar to that of thrust moraine. The morphology is hummocky to rolling with moderate to high relief. The thickness differs but is generally more than 3 m. This complex forms only a small part of the area.

MTU – Thrust moraine and undivided moraine complex; terrain in which the units are inseparable due to a similar appearance or to the small size of the areas covered by the individual units. The composition is similar to that of thrust moraine. The morphology is hummocky with low to moderate relief. The thickness differs but is generally more than 3 m. This complex forms only a small part of the area.

MU – Moraine, undivided; this unit includes terrain that either lacks the characterizing features to place it in any of the above subdivisions or, in a few areas, is a complex of three or more moraine types that are inseparable at the map scale. The material is mainly till but locally may include a small amount of sand, silt, clay, or gravel of glaciofluvial or glaciolacustrine origin. The morphology is hummocky to rolling and the relief ranges from flat to high. The thickness is generally more than 2 m. This unit forms a significant part of the terrain south and east of Wolf Lake (Tp 66, R 7); east, south, and southwest of Marie Lake (Tp 65, R 2); east of Cushing Lake (Tp 58, R 3); southeast of Garner Lake (Tp 60, R 12); west of Huppie Lake (Tp 64, R 13); east of Seibert Lake (Tp 66, R 9); and north of Spencer Lake (Tp 67, R 9).

MUF – Undivided moraine that includes what appears to be poorly developed flutes in some areas; the moraine is composed mainly of till and the morphology is hummocky to rolling with low to flat relief. The thickness is generally more than 2 m. This complex forms only a small part of the area.

MW – Washboard moraine; terrain composed of low relief, parallel to subparallel ridges of hummocks. The ridges are generally perpendicular to the glacial flow direction. The material is dominantly till with local small amounts of sand, silt, clay, or gravel. The morphology is rolling with low relief. This complex forms only a small part of the area. This unit is distinctly different in appearance from transverse moraine and is mapped separately because the two units are believed to have a different genesis.

Glaciotectonic features

Introduction

There have been a number of major glacial advances across the Central Plains of North America, the earliest likely about 2 million years ago (Fenton 1984c; Stalker, in preparation). All of these likely deformed the underlying substrate in places. The product of this glaciotectonic deformation is mapped as thrust moraine in the Sand River map area. The varieties of this terrain type are described below and include some types not previously recognized on the Plains.

Thrust moraine or deformation terrain is composed of masses of preexisting sediment (rock or unconsolidated Tertiary and Pleistocene sediment or both) that have been transported more or less intact by glaciers. Where present, associated depressions upglacier of the thrust features are also included in this terrain.

Glaciotectonic features are widespread within the glaciated part of the Plains and have been recognized in the provinces of Alberta, Saskatchewan, and Manitoba, and the states of North Dakota and Minnesota (Moran and others 1980). They are also present in other glaciated areas, for example, Indiana, Illinois, Ohio, and Pennsylvania (Moran 1971), Kansas (Dellwig and Baldwin 1965), England (Banham 1975), Holland (Ruegg 1981; Wateren 1981), Poland (Brodzikowski and Van Loon 1985; Brykcznski 1982; Drozdowski 1981; Ruszczynska-Szenajch 1976, 1978), and Denmark (Aber 1979, 1982; Berthelsen 1979; Schack Pedersen 1986, in press).

One of the earliest descriptions of the Great Plains was by Sardeson (1898, 1905, 1906) who interpreted several large outliers of Cretaceous rock in Minnesota as being blocks transported by glacier ice. Until recently the glaciotectonic features described were generally only large hills or ridges (longer than 1 km) composed mainly of rock (Hopkins 1923; Slater 1926, 1927; Byers 1960; Kupsch 1962; Christiansen and Whitaker 1976; Moran 1971). Within the last decade, progress has been made in recognizing the great extent and variety of this terrain: that there are small as well as large thrust masses, that they exhibit a great variety of geomorphic expressions, that they may be composed entirely of Quaternary sediment rather than bedrock, or a mixture of the two, and that the variety of internal structure is greater than previously recognized (Aber, personal communication; Moran and others 1980; Bluemle and Clayton 1984; Andriashek and Fenton 1982; Fenton and Andriashek 1978; Fenton 1983a, 1983b, 1984a, 1984b, 1987; Fenton and others 1984; Fenton, Langenberg and others 1985; Fenton, Moell and others 1985).

Three broad types of thrust moraine are recognized in the Sand River area: (1) the hill-hole pair, (2) hills with a fault-bounded depression, and (3) rubble terrain. This is a simplification of the five-part division suggested by Fenton and Andriashek (1978). These features are recognized primarily by using aerial photographs and, to a lesser extent, topographic maps.

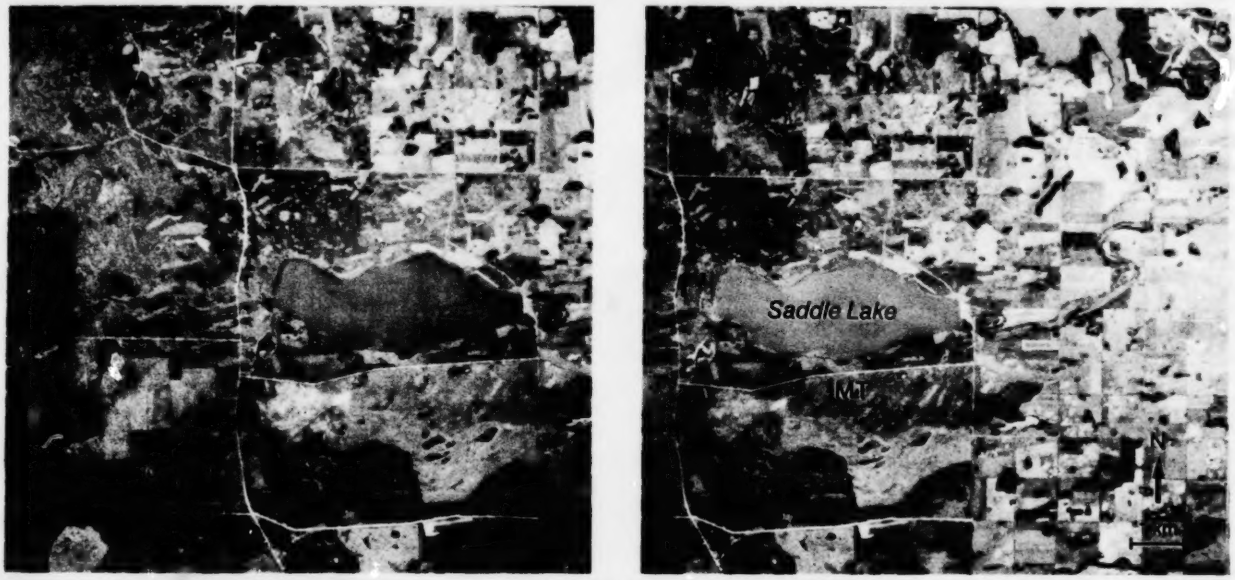


Plate 12. Hill-hole pair in the Saddle Lake area (Tp 58, R 11-12). Stereo aerial photographs showing the arcuate ridges forming the composite thrust ridge (MT) south of the lake and a small esker immediately southwest of the lake. Alberta Government photos: AS1111, line 39, numbers 30 and 31.

Hill-hole pairs: This terrain type consists of a hill and, directly up-glacier of this, a depression that in most cases contains a lake (plate 12).

Hill-hole pairs are widespread throughout the Sand River map area and form a major part of the thrust terrain. Many of the lakes in the area occupy depressions of this kind. The hill may be a simple featureless mound or a complex consisting of series of ridges oriented perpendicular to ice flow direction, such as the hill south of Saddle Lake (Tp 58, R 12, Fenton and Andriashek 1983, in pocket; and plate 12). There is a wide range in size, although the hills are generally between 20 and 50 m high and cover an area of about 5 to 10 km^2 each. Examples of these are south of Frenchman Lake and Iron Wood Lake (Tp 64, R 10), Touchwood Lake (Tp 67, R 9), and Spencer Lake (Tp 67, R 9).

Smaller features covering less than 1 km^2 and less than 20 m in relief are present but less common. Larger features are also less common. The largest thrust hills in the study area are located south of Muriel and Sinking lakes (Tp 58-59, R 5-6 and plate 13), and south of Cold Lake (Tp 63, R 1, W 4 Mer to R 27, W 3 Mer east of the Alberta-Saskatchewan border). The Muriel Lake thrust feature covers an area of about 140 km^2, is over 100 m in height, and in the western part exceeds 200 m in height. The source depression is partially filled by Muriel and Sinking lakes.

The Cold Lake thrust feature originally consisted of a ridge extending across the entire southern end of Cold Lake (Fenton and Andriashek 1983, in pocket). A subsequent southwestward readvance from Cold Lake removed much of the hill lying on the Alberta side of the border. The dimensions of the remaining ridge indicate that the entire ridge originally covered about 50 km^2 and exceeded 120 m in height.

Hills with fault-bounded depressions: This terrain type consists of a hill-hole pair in which the up-glacier depression is bounded on at least one side by a linear margin. This straight margin is believed to be the trace of a strike-slip fault created during the glacial excavation of the sediment.

This type of terrain is present in only a few areas: southwest of Wolf Lake (Tp 65, R 7), Primrose Lake (Tp 67, R 1-2), and Marie Lake (Tp 65, R 3). The Marie Lake thrust, for example, covers an area of about 35 km^2, exceeds 70 m in height, and contains about 2.5 km^3 of sediment.

The Wolf Lake thrust is the best example of this type of feature (plate 14 and figure 66). The thrust consists of a hill composed of a series of arcuate ridges. The hill is asymmetric with the steeper face on the south, the down-glacier side. The hill covers about 42 km^2, is about 140 m high, and contains about 6 km^3 of sediment. Fault scarps form the east and west margins of the lake and are parallel to the glacial flow direction (Fenton and Andriashek 1983, in pocket). A steep scarp about 10 m high forms the northeast, up-glacier side of the lake. The undisturbed terrain surrounding the thrust hill and depression is essentially flat.

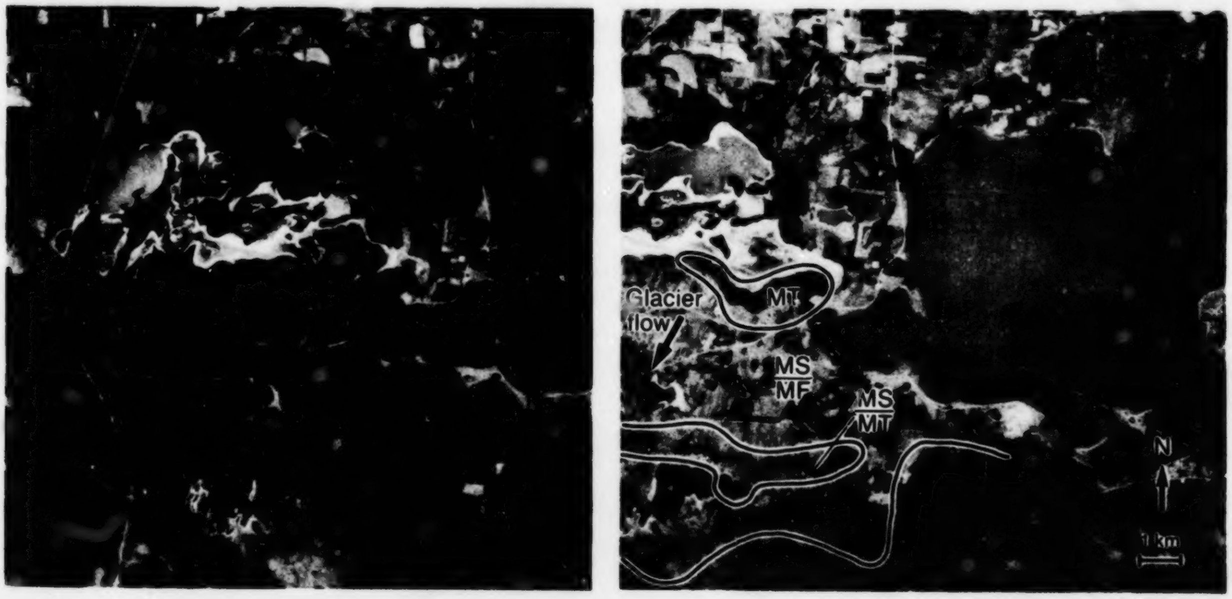


Plate 13. Thrust moraine in the Sinking Lake-Muriel Lake area (Tp 59-60, R 5-6). Stereo aerial photographs showing steep-sided depression formed by excavation of the sediment extending from north of Sinking Lake and Muriel Lake southward to the large ridge of thrust sediment along the southern part of photo. The Sinking Lake depression is partly occupied by the lake but the exposed portion reveals: (i) a relatively level surface with small ridges and hills of "relict" thrust debris (MT) that were not completely removed, (ii) fluting (MF) of both the level surface and in part the thrust debris, and (iii) thin discontinuous stagnant ice (MS) debris covering much of the depression. Alberta Government photos: AS1111, line 40, numbers 88 and 89.

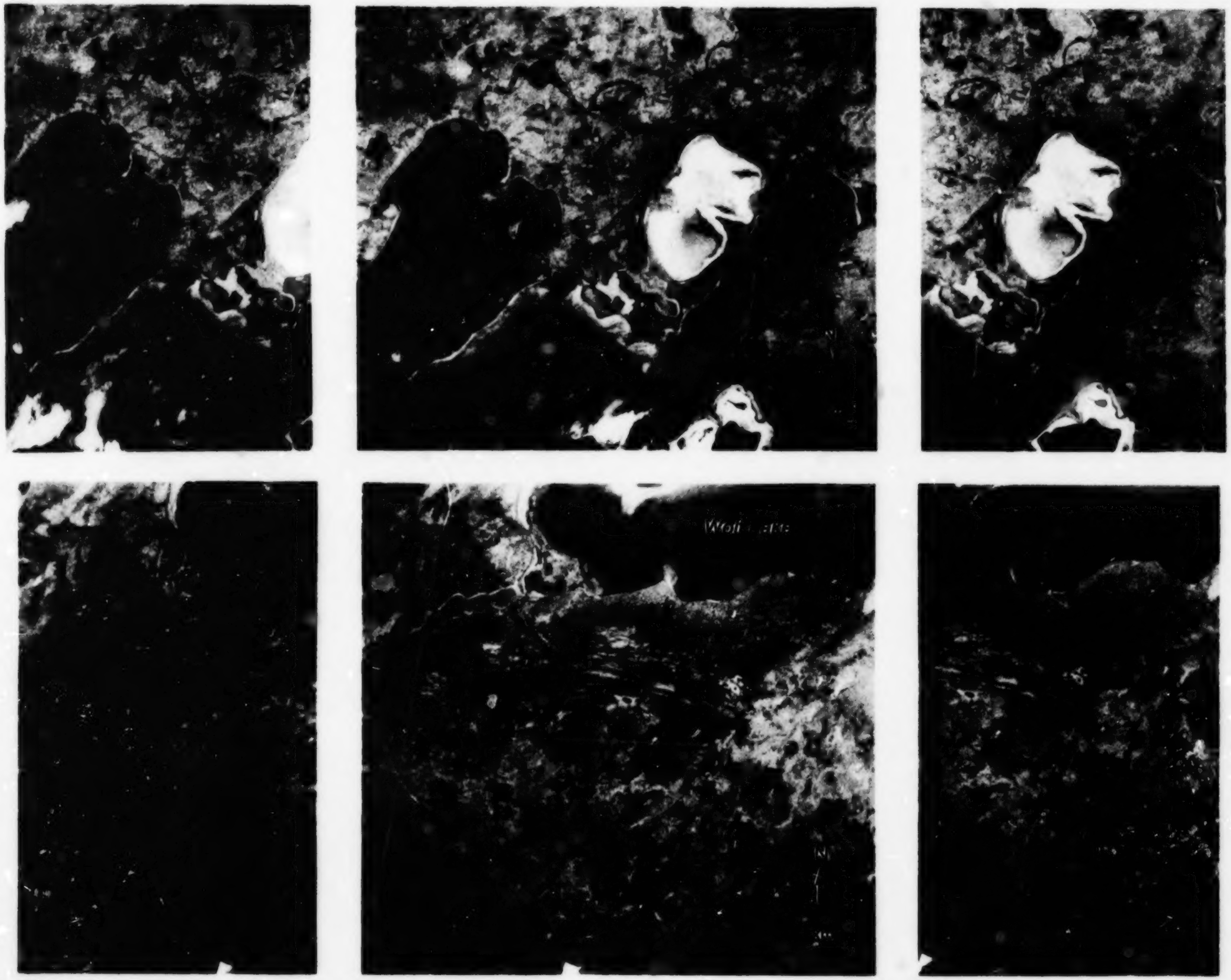


Plate 14. Wolf Lake thrust moraine (Tp 65-66, R 7). Stereo aerial photographs showing an example of a thrust hill with a fault-bounded depression. Note asymmetric shape of ridge, lying down-glacier and south of the lake, and the scarp along the east, west, and north sides of the lake. Alberta Government photos: AS116-5412, numbers 160-162, and AS117-5411, numbers 178-180.

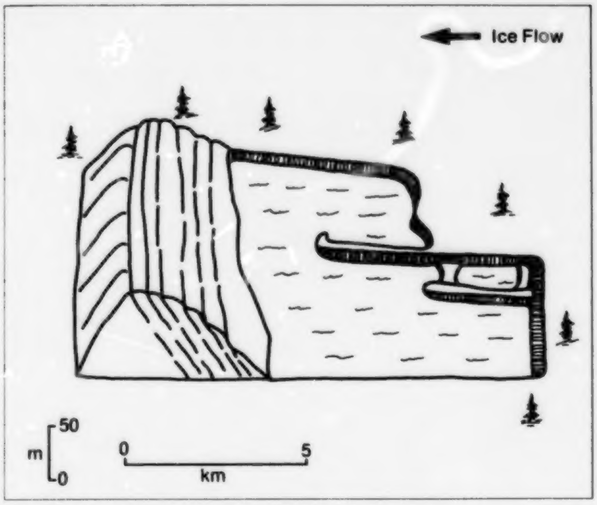


Figure 66. Schematic of the Wolf Lake thrust.

A subdivision of this type of terrain is produced where en echelon tear faulting creates an en echelon series of source depressions. This is illustrated in the Standish Lake area (figure 67) where an en echelon series consisting of four strike-slip faults forms the eastern boundary of a large composite source depression. A hill composed of arcuate ridges is situated on the flat terrain directly down-glacier of the easternmost subdivision of the depression, here called a subdepression. This hill (plate 15) covers about 12 km^2 and is about 100 m high. The subdepression associated with this hill covers about 16 km^2 and is about 2.5 km wide. The three additional subdepressions of similar width are situated in en echelon fashion to the northwest. The thrust hills originally associated with these subdepressions have either been completely or partially eroded and streamlined by glacier flow subsequent to the thrusting.

One other variation of fault-bounded terrain is found where the thrust sediment is completely removed, rather than being deposited down-glacier of the depression. This results in a depression with the sides (faults) parallel to the ice flow direction and an upstream margin that is perpendicular to the flow direction, producing an orthogonal pattern. In the Sand River area these depressions are generally filled with wetland sediment rather than water, indicating that they are shallower than the depressions up-glacier of hills. Conceivably, the ice may have removed only a relatively thin layer of sediment during the thrusting.

Rubble moraine: This terrain consists of a series of hills that form a train of debris down-glacier from a source depression. In the Sand River area the size of these hills decreases down-glacier from the depression. The hills are composed of a mixture of syngenetic till and distinct blocks of preexisting unconsolidated sediment and rock.

The best example of rubble moraine is found in what is herein named the Whitefish Lake Rubble Train. This unit extends from the north end of Whitefish Lake (Tp 62, R 13) southeastward to the edge of the map area (Fenton and Andriashek 1983, in pocket). The up-glacier source depression is filled by Whitefish Lake (plate 16). The western boundary is a scarp that is 50 m high in the Whitefish Lake–Garner Lake area and 30 m high in the Mann lakes area further south. The eastern boundary grades eastward from undisturbed thrust moraine to fluted thrust moraine formed by overriding and partial remolding of the thrust sediment, and finally to typical fluted terrain composed of long streamlined ridges formed by complete remolding of the thrust sediment (Fenton and Andriashek 1983, in pocket).

The size of the hills in the Whitefish Lake Rubble Train decreases down-glacier over a distance of about 50 km, beyond which the terrain is essentially flat. South of Whitefish Lake, in the northern one-third of the rubble train, the hills are large, generally over 1 km^2 in area and over 30 m in relief (plate 16a), in places showing the arcuate pattern of ridges. Southward, down-glacier, in the central one-third of the train around Upper and Lower Mann lakes, the hills are smaller, generally less than 0.3 km^2 in area and about 10 to 15 m in height (plate 16c). About 4 km further southward the train consists of small, low hummocks less than 0.12 km^2 in area and less than 7 m in height.

The lateral extent and the original shape of this rubble train is unknown because the erosion and streamlining which produced the fluted moraine along the eastern boundary of the thrust moraine also removed some portion of the rubble.

Internal composition and structure of thrust moraine

The data on the internal makeup of these thrust features are limited due to the small number and size of the sections, usually road cuts, that have been exposed. The few thrust hills that are accessible exceed the maximum drilling depth of 60 m of the power auger rig used during the study, and the thrust depressions are generally either water-filled or inaccessible to the drill rig.

The data allow a description of the types of features that may be present in the thrust moraine but do not permit the construction of a clear picture of any particular feature.

The composition of thrust sediment is highly variable. At a given location this sediment may consist of two or more of syngenetic till, preexisting till, sand, silt, clay, sandstone, ironstone, or mudstone. The proportion of bedrock in the thrust sediment is controlled mainly by the thickness of the preexisting Pleistocene sediment. Pleistocene sediment is generally over 50 m thick in the Sand River area, and as a result many of the large thrust hills are likely composed entirely of glacial sediment; the Marie Lake and Wolf Lake thrusts, for example, consist of displaced Marie Creek till. The known exceptions are: the thrust hills south of Cold Lake which contain a large proportion of claystone and ironstone, the thrust terrain north and west of Touchwood Lake where claystone is present in some of the road cuts, and northeast of Whitefish Lake where claystone and sandstone are exposed in road cuts. The hills of the hill-hole pairs tend to contain less variable sediment than that within the rubble train. This is likely due to a shorter transport distance and therefore less mixing of the excavated sediment and the debris already entrained within the glacier.

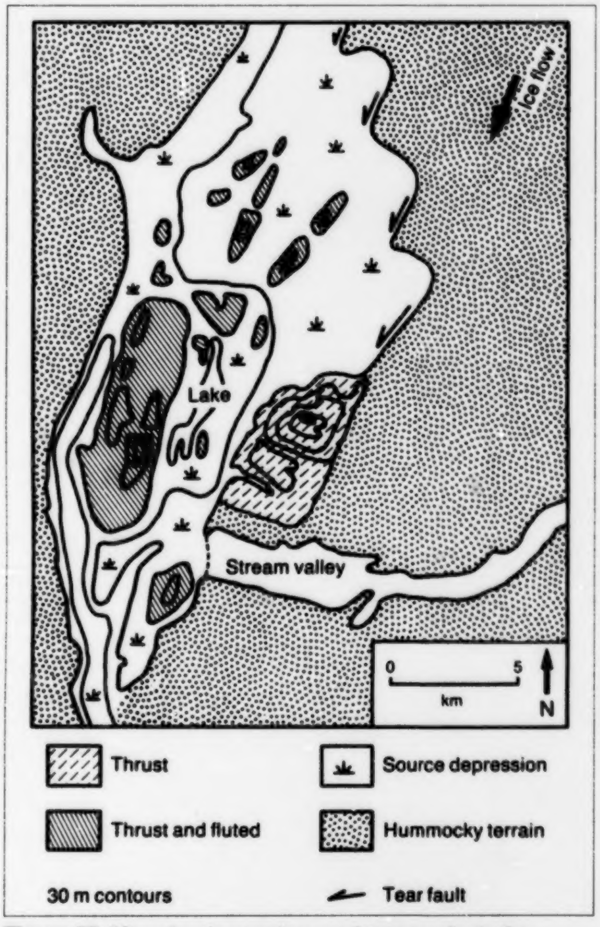


Figure 67. Map showing geology and topography in the vicinity of the Standish Lake thrusts. En echelon tear faulting resulted in a series of southwest trending subdepressions. Note that the hill of thrust sediment is intact south of the easternmost subdepression, but that other hills have been partially eroded to form fluted terrain.

A section in the rubble moraine near the Mann lakes shows syngenetic till, older till, sand, silt, and bedrock (plate 6b). These blocks of preexisting Pleistocene sediment and Cretaceous rock show signs of deformation including folding and elongation.

In summary, thrust moraine, or glaciotectonic or deformation terrain, is widespread on the Central Plains of North America. The Sand River area contains a variety of deformation landforms previously undescribed. These can be divided into three broad groups: hill-hole pairs, hills with fault-bounded depressions, and rubble moraine. The composition of the thrust sediment is varied and known to include, at any particular site, two or more of syngenetic till, pre-existing till, sand, silt, clay, sandstone, ironstone, or claystone. Many of the features are composed entirely of preexisting Pleistocene sediment.

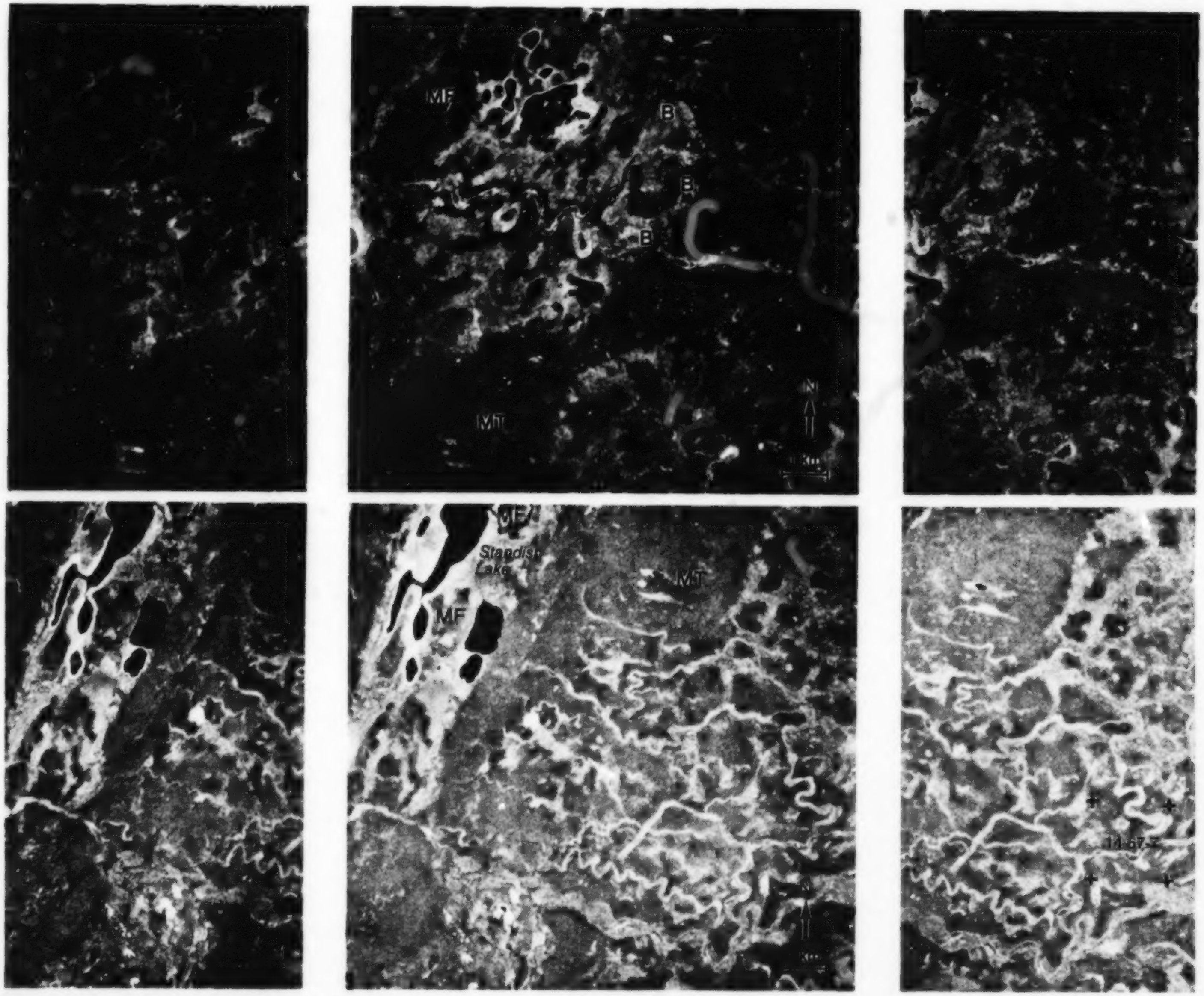


Plate 15. Standish Lake thrust area (Tp 67-69, R 7-8). Stereo aerial photographs show that en echelon tear faulting has resulted in a series of subdepressions trending southwestward in an en echelon fashion. Note that the hill of thrust sediment (MT) is intact south of the easternmost depression (B) but that others have been eroded or partly eroded to form fluted terrain (MF). Energy Mines and Resources photos: A24453, numbers 14-16, and A24453, numbers 75-77.

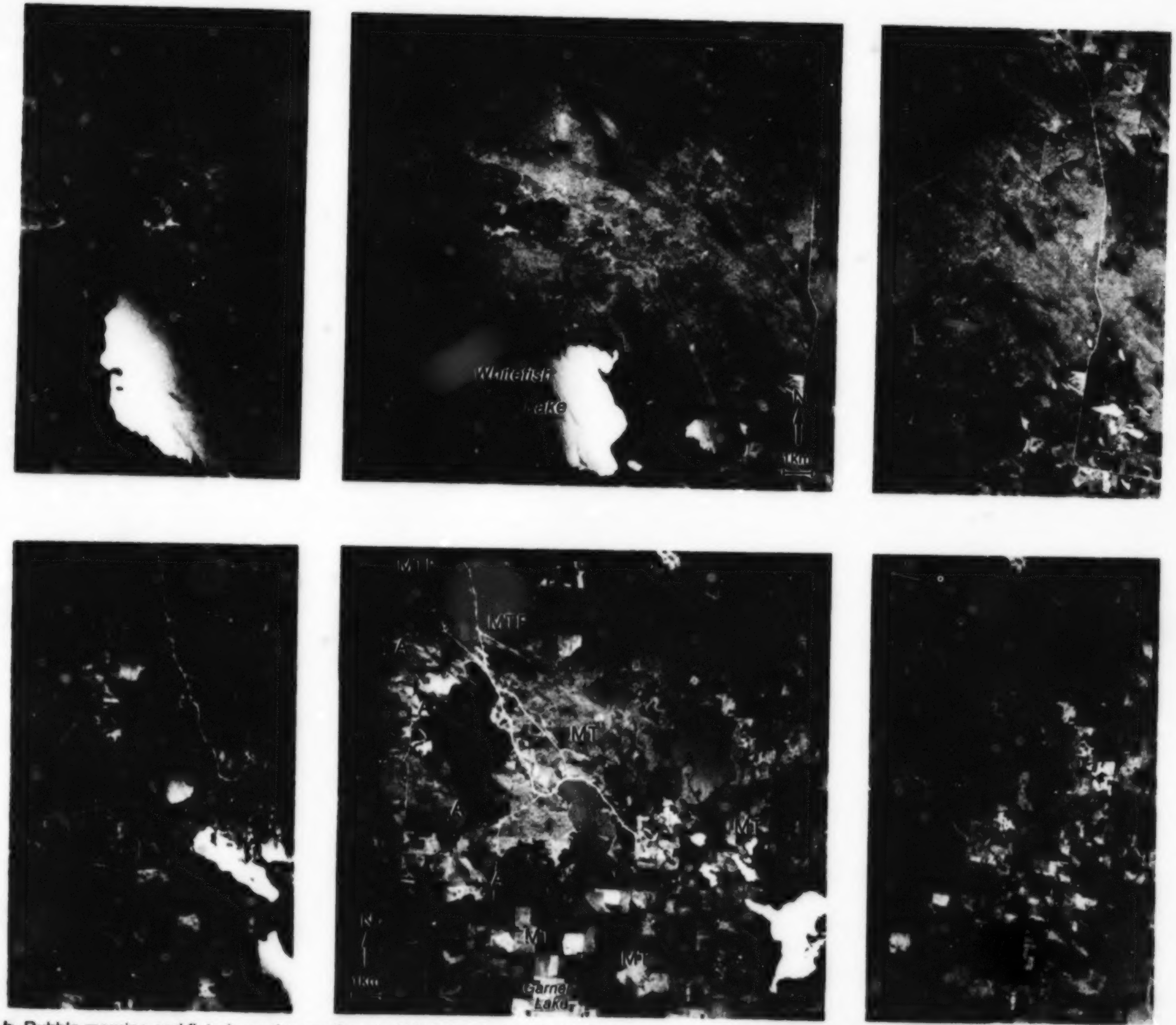

Whitefish
Lake
N
1Km
MTF
MTF
MT
MT
MT
MT
A
A
A
N
1Km
Garner
Lake

Plate 16a,b. Rubble moraine and fluted moraine southeast of Whitefish Lake (Tp 62, R 13 to Tp 59, R 10). Stereo aerial photographs showing from the north to the south: (a) Whitefish Lake area, (b) Garner Lake area, and (c) Mann lakes area (next page). Note down-glacier decrease in the size of the hills. Alberta Government photos: AS1111, line 41, numbers 130-133, and AS1111, line 42, numbers 181-183.

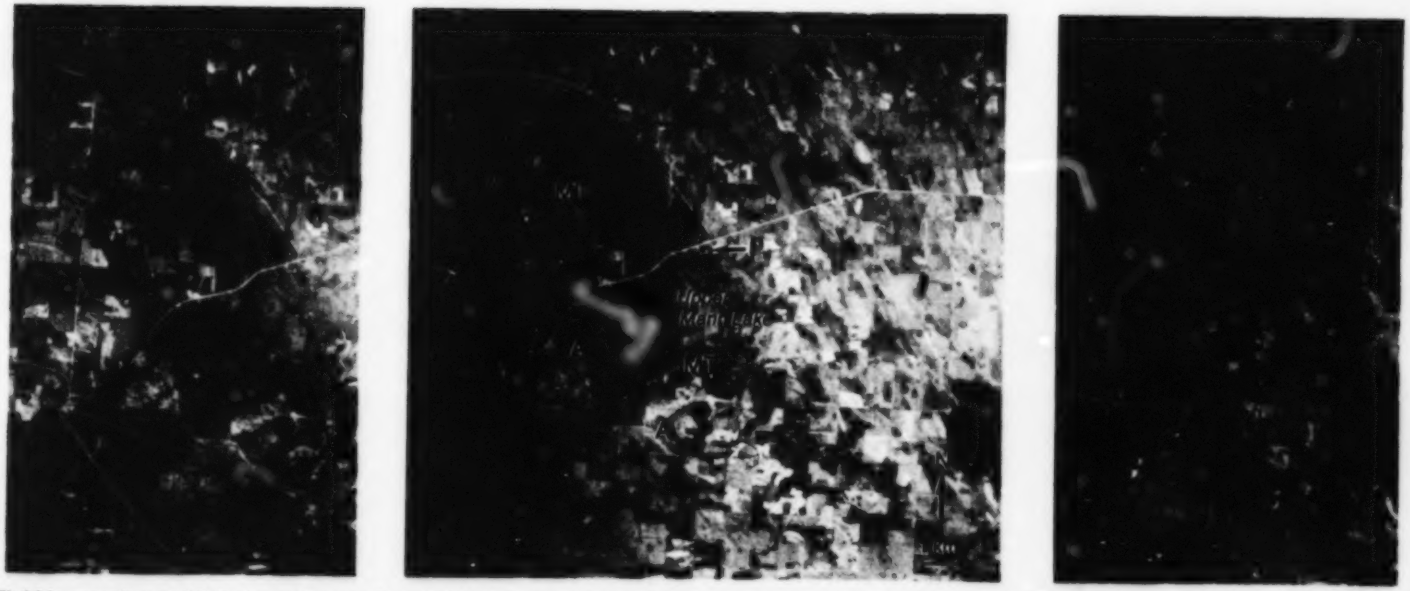


Plate 16c. Rubble moraine and fluted moraine southeast of Whitefish Lake (Tp 62, R 13 to Tp 59, R 10). Stereo aerial photographs showing Mann lakes area. Note down-glacier decrease in the size of the hills. Arrow "P" shows location of plate 6b. Alberta Government photos: AS1111, line 40, numbers 81-83.

Economic and engineering aspects of surficial geology

This section of the report highlights three categories of surface geologic materials that are considered to have significant economic and environmental importance (Fenton and Andriashek 1980). These include aggregate resources, construction-fill material, and buried aquifers. The following provides a focus for future detailed resource evaluations similar to the one recently completed for the aggregate resources in the Edmonton/Lloydminster region (Edwards and others 1985).

Aggregate resources

Aggregate resources in the Sand River map area are predominantly glaciofluvial sand with lesser amounts of gravel. Figure 68 summarizes the known distribution of surface or near-surface sand and gravel deposits, shown in larger scale on the 1:250 000 map (Fenton and Andriashek 1983, in pocket). In general, gravel is confined to upper terraces along the major drainage systems, notably the Beaver River, Moose Lake River, and Medley River in the central and northeastern parts of the map area. A significant deposit is also located within an abandoned meltwater channel south of the present confluence of the Beaver and Sand rivers.

Widespread areas of glaciofluvial sand, and possibly gravel, are located along the following: (1) the upper terraces of the southern end of the Sand River (Tp 63, R 8), extending southeastward to the south shore of Moose Lake, including channel margins of the Moose Lake River, the glacially thrust sand generally west of Stebbing Lake (Tp 60-62, R 7; NE 1/4, Tp 62, R 8; S1/2, Tp 63, R 8), and an abandoned channel segment trending north-south through Minnie Lake (Tp 60-62, R 8); (2) the glacially thrust sand near the Owl River north of Lac La Biche (Tp 69, R 13); and (3) within an outwash plain flanking the southern margin of the Beaver River in the east (Tp 62, R 3) and within a meltwater channel extending east from Barbara Lake in Tp 64, R 6, to Ethel Lake in Tp 64, R 2 (figure 68).

Elsewhere in the northeastern part of the map area, sand lies within numerous meltwater channels that dissect a hummocky stagnant-ice moraine. Access to these deposits is restricted because they lie within the Department of National Defense Air Weapons Testing Range.

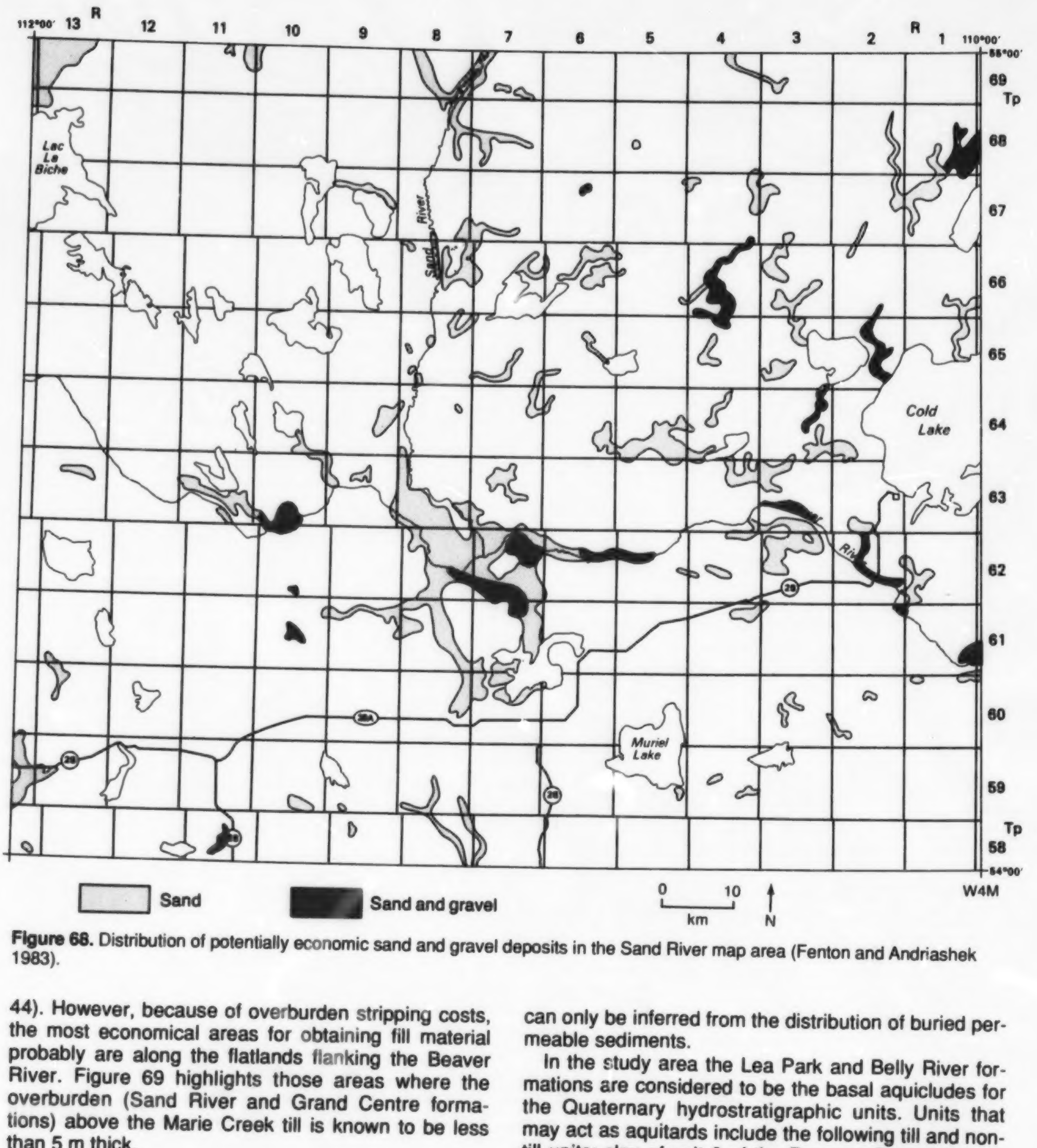
An estimate of the current and future demands placed on the sand and gravel resources in the southern part of the Sand River map area is included in the aggregate resources report for the Edmonton/Lloydminster region (Edwards and others 1985). The report provides distribution maps of the known deposits, projection figures for future demands, and tabulated data such as the total number of deposits in each county, type of material, thickness, overburden thickness, area of deposit, and quantity.

Construction fill material

Till is preferable fill material, compared to sand, silt, or clay, mainly because its well-graded grain size makes it more easily excavated, emplaced, compacted, and trafficable under moist to wet conditions. Some tills are more suitable as fill material however, because of differences in such properties as grain size, amount of coarse clasts, degree of consolidation, fracture density, and moisture content. Till with more desirable properties may be mined preferentially, even at the exclusion of till that lies at the surface but which has less desirable properties. For example, geotechnical studies in central Saskatchewan (MacDonald and Sauer 1970) demonstrate that an upper soft, compressible till, correlated with till in the Battleford Formation (Christiansen 1968), overlies a very dense, hard, but fractured till in the Floral Formation. Where unfavorable moisture conditions exist, the upper till "was found to be extremely difficult to excavate because of excessive deformation under the wheels of construction equipment, and equally difficult to place and compact in the roadway embankment" (MacDonald and Sauer 1970, 117). Excavation of the upper till was further hindered by the presence of a widespread boulder horizon at the base of the unit.

Similar observations were made of the till in the Sand River area (Andriashek and Fenton 1982). In the eastern part of the map area, the surface till of the Grand Centre Formation is softer, more clayey, and moister than the underlying sandy, weathered and fractured, and dense Marie Creek till. A boulder horizon is commonly recognized at the base of the Grand Centre Formation as well. As shown in table 12, these units are interpreted to correlate with the Battleford and Floral formations in Saskatchewan. In 1976 it was observed that the town of Grand Centre preferentially used the Marie Creek till as fill for roadway construction. The properties that make the Marie Creek till more favored likely relate to the following: (1) it is sandier and contains more granules and pebbles, which makes it less plastic, better drained and drier; (2) the upper part is fractured and weathered, which causes the moist material to spall off in shards or prisms, rather than as a sticky mass, when excavated; and (3) the till is harder and denser, possibly due to overconsolidation by glacial overriding and dessication of the upper weathered surface.

The most geologically favored source area for the Marie Creek till is in the northeastern part of the map area. Here, the oxidized, fractured horizon on the till surface is widespread and the till is most sandy (figure


112°00′
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13
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69
Tp
68
67
66
65
64
63
62
61
60
59
Tp
58
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Lac La Biche
Sand River
Cold Lake
Beaver River
Muriel Lake
28
28A
Sand
Sand and gravel
0
10
km
N
W4M

Figure 68. Distribution of potentially economic sand and gravel deposits in the Sand River map area (Fenton and Andriashek 1983).

44). However, because of overburden stripping costs, the most economical areas for obtaining fill material probably are along the flatlands flanking the Beaver River. Figure 69 highlights those areas where the overburden (Sand River and Grand Centre formations) above the Marie Creek till is known to be less than 5 m thick.

Buried aquifers and aquitards

This section describes the potential aquifers and aquitards in the Pleistocene stratigraphic sequence in the Sand River area. Aquifer tests were not conducted for any of the units; therefore, the groundwater potential can only be inferred from the distribution of buried permeable sediments.

In the study area the Lea Park and Belly River formations are considered to be the basal aquicludes for the Quaternary hydrostratigraphic units. Units that may act as aquitards include the following till and nontill units: clay of unit 2 of the Empress Formation, the Bronson Lake till, the Bonnyville till, silt and clay of the Ethel Lake Formation, the Marie Creek till, and the Grand Centre till. The major aquifers include the following units: units 1 and 3 of the Empress Formation, the Muriel Lake Formation, sand and gravel of unit 1 of the Bonnyville Formation, sand and gravel of the Ethel Lake Formation, and the Sand River Formation.

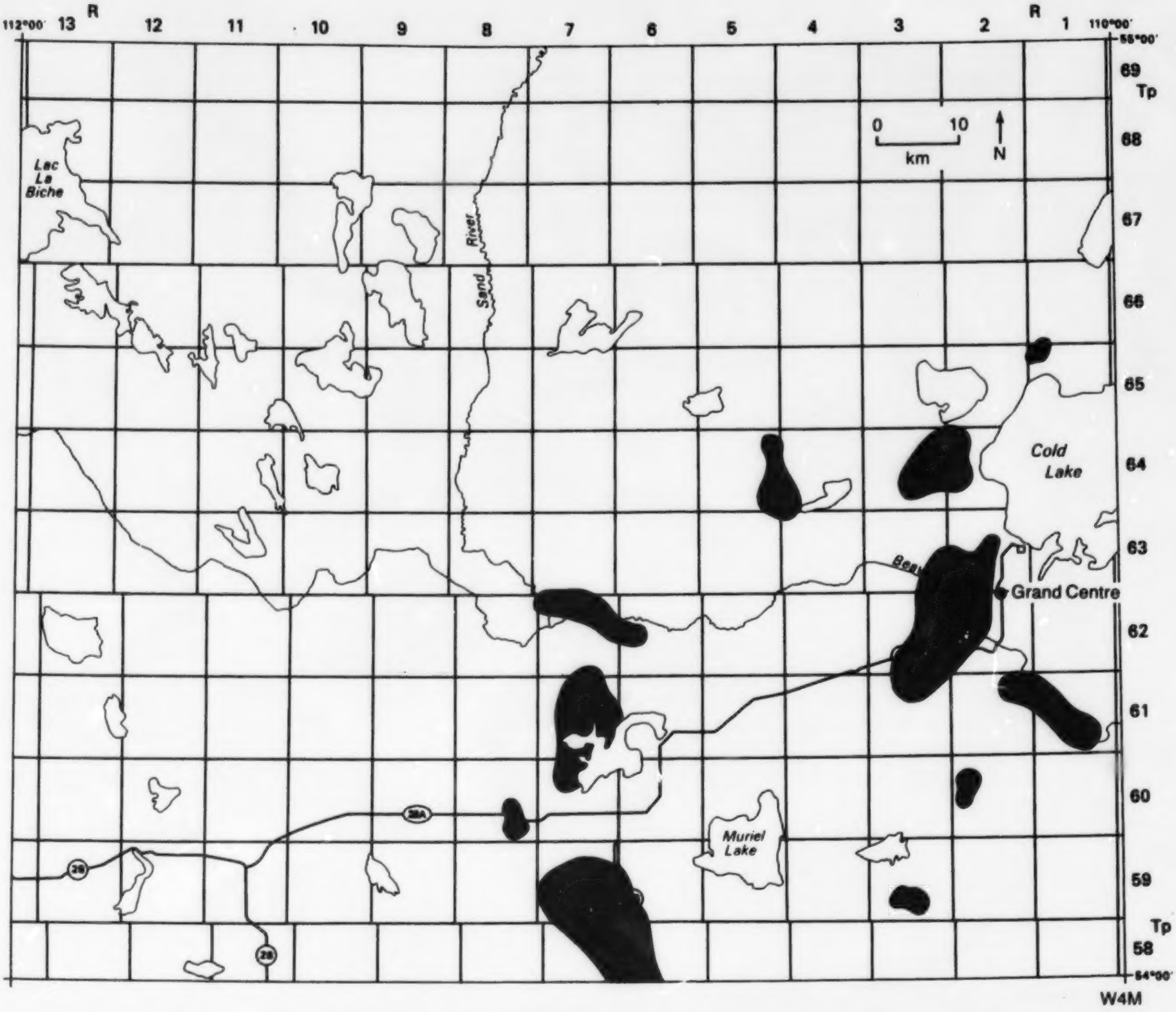

Figure 69. Areas of thin overburden (<5 m) on till of the Marie Creek Formation. The most desirable area for fill is near the town of Grand Centre where the overburden is thin and the Marie Creek till is sandier.

The most widespread till aquitards are the Bonnyville and Grand Centre formations which cover most of the study area. The Marie Creek till is absent in the southwest and is less widespread. The Bronson Lake Formation is present only in segments of the buried valleys. The non-till aquitards also have limited extent within the map area. Silt and clay of the Empress Formation lie mainly in segments of the major preglacial valleys, whereas much of the silt and clay of the Ethel Lake Formation lie above the bedrock interfluves in the southeast and west-central parts of the study area.

Unit 1 of the Empress Formation and the Muriel Lake Formation are considered to have the highest potential as aquifers. Both are composed of thick sand and gravel and are widespread in the study area. Aquifers with a great local potential are the following: (1) sand and gravel that lie between the two till units of the Bonnyville Formation in the northeast above the buried Sinclair Valley; (2) sand and gravel of the Ethel Lake Formation, which are commonly interbedded with silt and clay and have a limited extent; and (3) stratified deposits of the Sand River Formation, which are more widespread but generally thin.

Figure 70 shows those areas where erosion or nondeposition of the intervening aquitards has allowed the superimposition of aquifers, resulting in the grouping of two or more stratigraphic units into a single hydrostratigraphic unit. For example, in the Empress Formation sand and gravel of unit 3 cannot be easily differentiated from sand and gravel of the underlying unit 1 if the silt and clay of the intervening unit 2 is absent, and therefore the unit can be considered a single aquifer. One can, however, infer the direct superposition of younger unit 3 sand and gravel in those areas

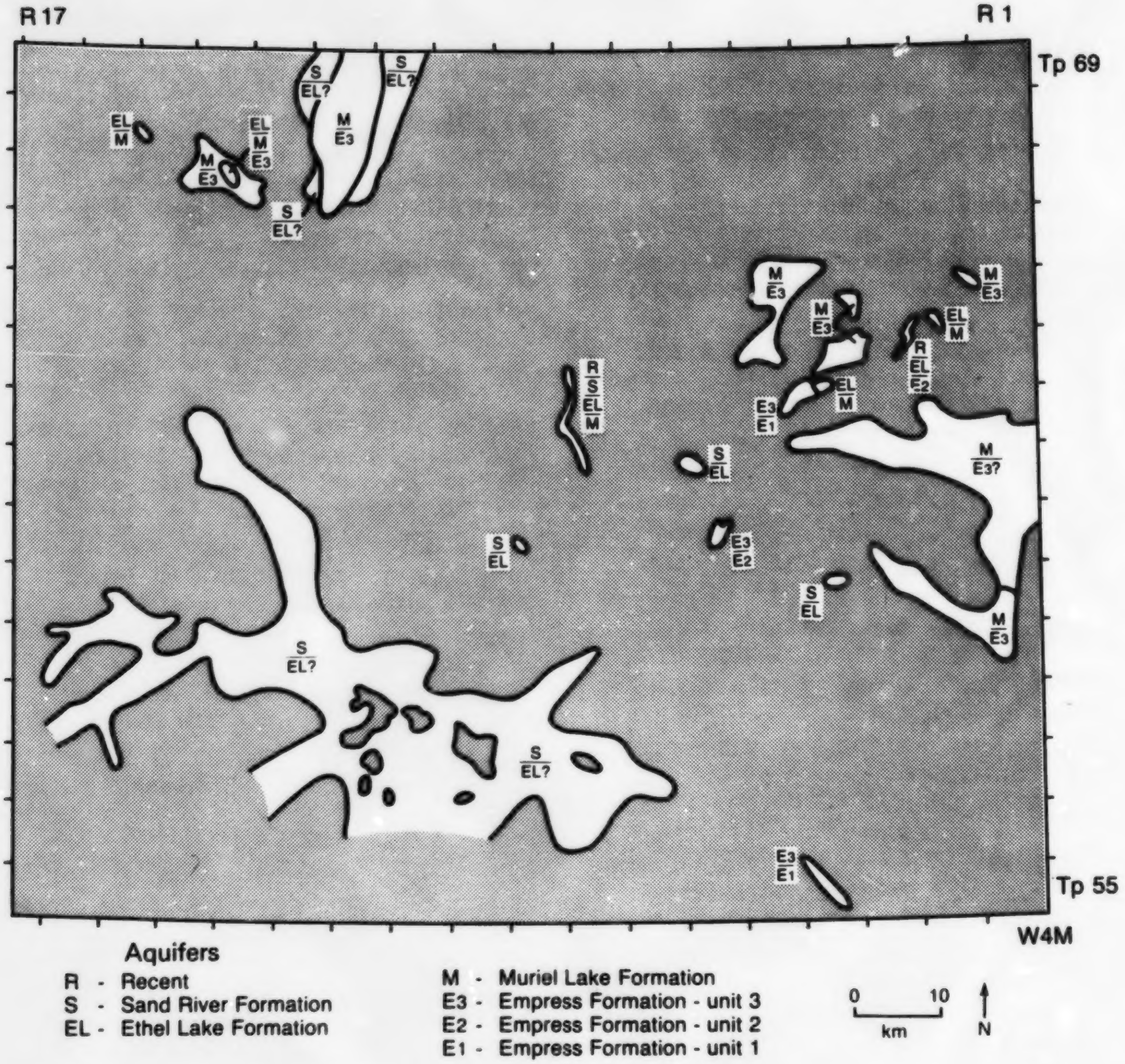
R17
R 1
Tp 69
Tp 55
W4M
S/EL?
M/E3
EL/M
EL/M/E3
M/E3
S/EL?
M/E3
EL/M
R/EL/E2
R/S/EL/M
E3/E1
EL/M
M/E3?
S/EL
E3/E2
S/EL
S/EL
M/E3
S/EL?
S/EL?
E3/E1
Aquifers
R - Recent
S - Sand River Formation
EL - Ethel Lake Formation
M - Muriel Lake Formation
E3 - Empress Formation - unit 3
E2 - Empress Formation - unit 2
E1 - Empress Formation - unit 1
0 10
km
N

Figure 70. Map of the Sand River study area showing regions where the absence of aquitards and aquicludes in the Quaternary stratigraphic sequence allows the superimposing of aquifers.

where the elevation and total thickness of unit 1 becomes significantly greater than that of the surrounding deposits. One such example is found along segments of the buried Beverly Valley in the east-central part of the map area where unit 3 of the Empress Formation directly overlies unit 1 (figure 70). Other examples of superimposition are the following: in the east where the Bronson Lake aquitard has been eroded and the Muriel Lake aquifer directly overlies unit 3 of the Empress Formation (figure 70); and in the southwest and northwest where the Marie Creek till is absent, and where stratified sediments of either (or both of) the Ethel Lake and Sand River formations lie between the Bonnyville and Grand Centre aquitards.

Those areas in the east and northwest designated in figure 70 by a question mark (?) following E3 indicate areas where sand and gravel lie beneath the Bonnyville till and on top of the bedrock surface. On the basis of stratigraphic position, these deposits are classed as unit 3 of the Empress Formation. However, on the basis of elevation, this permeable sediment is more likely sand and gravel of the Muriel Lake Formation, extending out of the buried Vermilion Valley and Bronson Lake Channel and onto the bedrock surface. For this reason, both units are shown in the figure, even though it is probable that only the younger unit, the Muriel Lake Formation, is present.

During retreat of the last glacier in the map area, glacial meltwater downcut and infilled a number of channels with stratified sediment. These stratigraphically younger deposits overlie, and may possibly be in contact with older aquifers within segments of the

Sand River and Marie Creek channels in the central parts of the map area (figure 70).

Glacially deformed terrain

Thrust moraine or deformation terrain is widespread in the Sand River area (Fenton and Andriashek 1983, in pocket) and can have ramifications for resource development. The sediment in thrust moraine is likely to be weaker than the other types of moraine and undeformed bedrock and includes both abrupt, lateral, and vertical changes in sediment type and incipient failure planes in the form of folds, faults, and glacial shear planes. The result of this is that excavations cut into this sediment have a greater tendency to fail and the material excavated may be highly variable.

Knowledge of geomorphology, geology, and groundwater is essential for determining the location of thrust moraine and evaluating the potential for failure. Foreknowledge of this type is of value for both planning and managing resource development.

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Appendix A. Description of field observations, laboratory procedures, and analytical methods

Field observations

Listed below are the observations typically recorded for both outcrops and auger samples.

(1) Color – Color was recorded for weathered and oxidized, and unweathered and unoxidized parts of outcrops and test hole samples. The colors of weathered outcrops were recorded from the exposed surface material, not recently excavated cuts. Colors of the units were compared to the Munsell Soil Color Chart.

(2) Grain size – A field estimate was made of the dominant grain size of the smaller-than-2-mm fraction of the till (for example, clayey-sand till, in which sand is the dominant grain size). The percentage of granules (2 to 4 mm) and pebbles (greater than 4 mm) was also estimated. Related to grain size is the moisture content, which was expressed as dry, moist, or wet. Moisture content affects the ease of digging or drilling.

(3) Pebble lithology – Only easily recognized differences in the pebble lithology were recorded. Drill samples commonly did not contain sufficient pebbles for meaningful counts.

(4) Joint or fracture density – Joint or fracture planes were recorded from outcrops only. The density of the fractures, their shape, size, and presence of secondary mineralization along the surfaces were noted, but not accurately measured.

(5) Stratification, laminations, partings – These structural elements were recorded for both outcrops and auger samples. Bedding and partings are visible in auger samples even though they are twisted and distorted by the drilling process.

(6) Inclusions of glacially displaced sediment – Masses of glacially displaced and incorporated older sediment are more easily recorded in outcrop but can also be recognized in auger samples if the displaced material is lithologically distinct from the host material.

(7) Boulder concentrations – Boulder concentrations were observed mainly in outcrops, although, if the boulder concentration was dense, boulders may have been encountered in drilling.

(8) Pebble orientations (in till) – In this study pebble orientations were measured in only one outcrop.

(9) Nature of contacts – The nature of the contact between units was recorded in both outcrop and auger-sample descriptions.

Laboratory procedures

The stages from sample collection to computer generated data plots are depicted in figure 6. Following is a description of the methods used to characterize the till units in the Sand River area.

A. Lithologic properties

Color

Color was used successfully to differentiate tills in the Sand River map area. Colors were recorded from weathered and unweathered units in outcrop, as well as from samples from the auger, in a moist state, using Munsell color charts. Weathered units in the Sand River map area are commonly much lighter brown, compared to dark gray of unweathered units. This is probably due to the oxidation of iron-oxide particles in the sediment. Units that show oxidation throughout the entire sample and not only along fracture surfaces, are referred to in this study as being oxidized. In most places these units were interpreted to have been exposed to surface weathering at one time, especially where unoxidized till overlies oxidized till; in these places the oxidized zone is considered to represent a weathered surface on the lower till. This interpretation was not applied, however, to oxidized sand units that transmit surface oxygen-rich water to buried units at depth.

Grain size

The determination of the grain size of till is a method commonly applied in Alberta to characterize and differentiate till units (Westgate 1969; Pawluk and Bayrock 1969; Fenton and Dreimanis 1976). This method can be successfully applied in the Sand River area as well. In this study grain size was calculated from the smaller-than-2-mm fraction of the till: percent total sand (0.063 mm to 2.00 mm), silt (0.004 mm to 0.063 mm), and clay (smaller than 0.004 mm). The Alberta Research Council laboratory uses the hydrometer method to determine the clay content, but the method is a slightly modified version of the A.S.T.M. (1954) procedure for grain-size analysis. The values obtained by the Survey's procedure were found to differ little from those obtained by the A.S.T.M. procedure, and reduced the analytical time required. The fundamental difference between the two methods is that the Survey's laboratory uses a computer program to determine the silt-clay boundary, based on only the 2, 4, 8, and 24 hour hydrometer readings. This program then plots the clay curve from these four data points.

Dry sieves and an electronic balance were used to calculate the percentage of sand, using the conventional A.S.T.M. procedure. The very-coarse-sand fraction was extracted to determine the amount of very coarse sand in the till, and was later stained with Alizurine red dye to determine the petrologic composition. This procedure helps differentiate limestone from dolostone (Friedman 1959). It was found that in the Sand River area differences in the amount of very coarse sand could be used to differentiate some of the till units, even those with similar grain sizes. The very-coarse-sand fraction can also be easily seen in hand samples and this enabled a preliminary differentiation in the field. The quantitative value of this estimated amount of very coarse sand was calculated later in the laboratory, and used to calibrate the initial field estimate.

Moisture content
The moisture content of a till, expressed as a percentage of the weight of a sample, was found to vary proportionally with the amount of clay. The method is simple to perform and can be easily applied in the field to determine the percentage of water in a sample and to provide a comparative value of clay in the sample. The method involves weighing a moist till sample in the field, drying the sample at a temperature no greater than 70°C and weighing the dry sample to determine the amount of water lost. The results of this technique were not used intensively to estimate the amount of clay, mainly because the clay contents were determined by grain-size analyses in the laboratory.

B. Petrologic and mineralogic properties

1. Petrologic composition of the very coarse sand

A method that was successfully applied to differentiate and correlate till units from small, disturbed samples such as test hole samples, involves the examination of the composition of the very coarse sand (1 to 2 mm) (Gross and Moran 1971; Fenton and Dreimanis 1976). This method was used to determine not only the till provenances, but also the source and direction of glacier flow. By the process of trial and error, approximately 300 grain counts per sample proved to be sufficient to represent all rock types in a till sample and this quantity was reasonably quick to count. For most of the till units in the Sand River area, the 1-to-2 mm fraction, extracted during the grain-size analyses, provided about 300 sand grains. The sand grains were separated into six petrologic categories: igneous and metamorphic rock, quartz, quartzite and quartz sandstone, carbonate rock, local rock, and miscellaneous rock. Following is a brief discussion of how these rock types were identified.

a. Igneous and metamorphic rock: This category consists of those rock types derived primarily from the Canadian Shield. These consist mainly of granite, gneiss and metasedimentary rock. The category includes both fine- and coarse-grained rock and may also contain some cordilleran volcanic rock which cannot be easily differentiated from the fine-grained igneous rock from the Shield. It is considered, however, that cordilleran igneous rock represents only a very small percentage of the total fine-grained portion. Fine-grained igneous rock constitutes only a small percentage of the total amount of igneous rock, so that any misidentification of a fine-grained rock has little impact on the calculation of the percentage of the other rock types.

b. Quartz: This category consists of almost all quartz grains irrespective of size, shape, roundness, or degree of transparency. It includes clear and milky quartz, quartz grains with impurities, and angular to rounded quartz. Two exceptions to this are: quartz grains which have imprints of contact minerals showing cleavages, such as feldspar and hornblende, which indicate a probable igneous or metamorphic source; and single quartz grains that are spherical and which show quartz over growths – these grains are interpreted to have been derived from quartz sandstone.

c. Quartzite and quartz sandstone: This category makes up a small percentage of the total rock fragments in the till units in the Sand River map area. It includes both metaquartzite from the Rocky Mountains and orthoquartzite from both the cordillera and the Athabasca Formation in northeastern Alberta. Fragments of Athabasca Formation orthoquartzite are identified by the following: the 1-to-2 mm-sized grains are composed of smaller, silica-cemented quartz grains that form a moderately indurated grape-like cluster, and they have a mauve to pinkish iron-stained color. Fragments of the cordillera quartzite are commonly brownish to buff colored and are composed of well-cemented to annealed grains of quartz. If the 1-to-2 mm metaquartzite grains are fractured, they commonly break across the individual smaller grains, rather than only along the grain boundaries. Otherwise, the 1-to-2 mm metaquartzite grains are commonly well-rounded.

Also included in this category are individual large quartz grains that are spherical and which show quartz overgrowths. These are interpreted to have been derived from an orthoquartzite.

d. Carbonate rock: This category consists of two rock types: limestone and dolostone. There are two possible sources for the carbonate rock in the till units in the Sand River area. The first is preglacial fluvial sand and gravel on the floors of the major buried valleys that were eroded by glaciers. This preglacial sediment contains quartzite, chert, volcanic rock, and carbonate, which were eroded and deposited by rivers flowing east from the cordillera. The second source is Devonian carbonate that lies along the southwest margin of the Canadian Shield in northeastern Alberta. In the Sand River map area most of the carbonate rock in the till is derived from glacial erosion of the Devonian rock in northeastern Alberta. Only little, if any, of the car-

Appendix A. (continued)

bonate rock was derived from the Cordillera. The reason for this is that carbonate rock is not as durable as quart-zite and chert and does not survive the long transport distance along the river channels into eastern Alberta. If some carbonate rock did manage to survive transport, it is probable that the amount would be very small compared to other rock fragments. Evidence to support this comes from recent work done on the composition of preglacial gravel in the Edmonton area, west of this study area. The study shows that the gravel is composed of about 95% quartzite, 3 to 5% sandstone, about 1% conglomerate, and 0 to 1% carbonates (Edwards 1984, 220).

Limestone and dolostone are differentiated by their stained color, produced by Alizurine red S dye (Friedman 1959), and by the fragment appearance. When stained, limestones become bright red, which contrasts with mauve or purple of the dolostone. Limestone grains extracted from till samples are typically very rounded and commonly have an ovoid shape whereas dolostone grains have a blocky, angular shape, and a microcrystalline, sugary texture.

e. Local rock: This category consists of locally derived rock fragments. In the eastern two-thirds of the map area this includes mainly claystone and ironstone derived from the Lea Park Formation. In the western third of the map area this category includes sandstone, siltstone, claystone, coal, and ironstone derived from the Belly River Formation. Generally this category makes up a small percentage of the rock in the till units in the Sand River area.

f. Miscellaneous rock: This category consists of chert, gypsum crystals, and unidentified rock types. It makes up generally less than 1% of a sample, although in some samples as much as 15% of secondary gypsum crystals may be present.

2. Carbonate in the silt-clay fraction

The determination of the carbonate content in the silt-clay fraction, as a means to differentiate till units, has been used successfully by a number of researchers (Christiansen 1968b; Fenton and Dreimanis 1976). The method applied in this study uses the Chittick apparatus and procedure which was first designed and successfully applied to till analyses by Dreimanis (1962) and later adapted by Christiansen and Ross (1971).

Briefly, the Alberta Geological Survey's technique involves adding 10% HCl acid to the smaller- than-0.063-mm fraction of the till and measuring the volume of CO_2 gas released after the carbonate reacts with the acid. By measuring the volume of gas released as a function of time, the rate of reaction can be determined, and from this curve the percentage of calcite and dolomite can be calculated (Christiansen and Ross 1971).

Carbonate determinations of the silt and clay were done for only a number of selected reference samples of each till unit because the method is relatively time-consuming and because an estimate of the carbonate content of the till is provided by the counts of the carbonate in the very coarse sand.

3. Clay mineralogy

The X-ray diffraction method to determine the clay mineralogy (illite, kaolinite, smectite, chlorite) of till, was applied to only a number of reference samples of each unit (appendix C). The technique was applied to test its usefulness in differentiating till; with a few exceptions, it was not successful.

4. Miscellaneous studies

In many places within the Sand River map area the upper parts of the Lea Park and Belly River formations are composed of claystone and siltstone that are soft and difficult to differentiate from clay of Pleistocene age. For a number of test holes, a palynological examination was required to determine if clay samples were of Cretaceous marine origin or Pleistocene nonmarine origin. These analyses were performed by C. Singh of the Alberta Geological Survey who not only identified the species of the microflora, but also described their degree of preservation. A description of the degree of preservation is required because glaciolacustrine sediment could also contain eroded and redeposited Cretaceous pollen. Well-preserved pollen indicate that the sampled material probably was from in-place Cretaceous rock and not from redeposited sediment.

C. Geophysical properties

Geophysical properties proved to be very useful in correlating the stratigraphic units in the Sand River map area, especially in extending correlations into areas where samples could not be collected. The geophysical logs that were typically available in the map area are the electric logs, which record the self-potential and resistance of the different sediment types. Gamma-ray logs were also available for some of the test holes.

At a number of locations, electric logs have been recorded in rotary test holes that are adjacent to the Alberta Geological Survey's auger test holes, and these enable a comparison between the logs and the analytical data. Representative logs were chosen for each of the till units (previously defined by the analytical data), and these served as standards for correlating till from rotary test hole data in areas where analytical data were unavailable.

Appendix A. (continued)

The electric logs of the stratigraphic units appear to be affected by a number of factors. Typically, coarse-grained sediment such as sand and gravel have a high resistance, especially if it does not bear water. The presence of water and dissolved salts, however, reduces the resistance, and this can produce a log kick without a change in the lithology. Fine-grained sediment such as silt and clay generally shows less differences in its signatures; it has a very low resistance. Lithified silt and clay, such as marine claystone and siltstone of the Lea Park Formation, have an even lower resistance and higher self-potential. Presumably this reflects the more consolidated and cemented nature of the rock.

For the most part, electric logs from water well drillers operating in the Sand River area are sensitive enough to detect not only gross differences in sediment type, such as gravel and clay, but also subtle differences in the properties of till. Generally, the logs appear to record the major differences in grain size of the till, though other factors appear to influence the logs as well. One of these factors is the presence, or absence, of fracturing within the till; a high degree of fracturing at the top of a unit appears to produce a higher resistance than in the lower unfractured part. Other factors, such as more abundant carbonate within the till also appear to contribute to a higher resistance.

Appendix B. Ranges in composition of formations containing glacial diamicton (till)

Table 3. Bonnyville Formation: Unit 1

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite / Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
T23	15-22-64-6-W4M	10	29	1	44	2	1.4	0.2	11	1	60	4	36	4	2	1	1	1	1	0.5	1	0.6				
T38	4-36-64-7-W4M	10	32	2	35	2	1.4	0.2	11	<1	60	5	34	5	4	1	3	1	1	0.5	1	0.9				
		3	25	1	41	2	1.2	0.1	12	<1	58	3	35	3	3	1	2	1	1	0.5	1	0.9				
T73	9-6-65-7-W4M	5	35	2	41	1	2.1	0.1	11	<1	64	3	30	2	3	1	3	1	<1	0.2	1	0.4				
77SR21	10-18-63-12-W4M	6	21	3	47	4	1.1	0.1	14	4	64	4	28	4	3	1	2	1	1	0.4	1	0.9				
			n=34		n=34		n=34		n=34		n=34		n=34		n=34		n=34		n=34		n=34					
			N=4		N=4		N=4		N=4		N=4		N=4		N=4		N=4		N=4		N=4					
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.				
			28	6	42	4	1.4	0.4	12	1	61	3	33	3	3	1	2	1	1	0.2	1	0.2				

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)

n - total number of test hole samples of the unit

N - number of test holes in which unit is recognized

xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $$\sum_{1}^{s} \frac{xi}{s}$$

σ - sample standard deviation = $$\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $$\sum_{1}^{N} \frac{\mu i}{N}$$

S.D. - standard deviation of the sample means = $$\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$$

Appendix B. (continued)

Table 4. Bonnyville Formation: Unit 2

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite / Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
T5	2-16-59-3-W4M	4	36	2	36	1	2.0	0.4	11	1	59	4	32	4	4	1	2	1	2	0.6	2	0.6	9	1	0.39	0.08
T6	15-31-62-3-W4M	7	50	4	24	2	3.4	0.4	9	<1	57	2	30	2	4	2	4	1	1	0.6	3	0.3	12	1	0.40	0.06
T9	13-10-62-2-W4M	6	43	4	28	4	2.8	0.2	9	1	59	4	30	3	6	1	2	1	2	0.9	2	0.4				
T10	9-16-63-4-W4M	2	46	2	14	3	3.2	0.4	11	1	69	2	22	2	4	1	3	1	<1	0.4	2	0.1				
T11	9-14-62-5-W4M	11	53	2	22	2	2.9	0.3	12	1	60	3	32	3	3	1	2	1	1	0.5	2	0.8				
T12	4-4-62-4-W4M	26	51	4	23	3	3.1	0.5	11	1	60	4	32	4	4	1	2	1	<1	0.2	2	0.7				
T13B	1-30-60-2-W4M	8	47	6	26	3	2.4	0.4	9	1	60	3	32	3	3	1	2	1	1	0.5	2	0.8				
T15	16-20-60-1-W4M	2	53	1	17	1	3.3	0.2	11	-	56	-	36	-	3	-	2	-	<1	-	2	-				
T16	4-30-61-1-W4M	4	51	4	22	1	2.9	0.3	9	-	57	2	34	3	4	<1	3	1	<1	0.2	2	-				
T17	7-36-61-3-W4M	7	43	5	33	5	2.7	0.5	10	2	55	2	37	4	3	1	2	1	1	1.0	2	1.0				
T18	9-18-61-3-W4M	3	51	2	24	2	2.6	0.5	11	1	63	3	31	3	4	<1	2	1	<1	0.4	1	0.3				
T19	16-30-64-2-W4M	19	48	3	24	2	3.0	0.3	-		52	4	41	3	2	1	1	1	1	0.6	2	0.7				
T20	1-26-64-5-W4M	27	45	1	31	1	2.8	0.2	9	<1	66	3	29	2	2	1	2	1	<1	0.2	1	0.4				
T22	7-19-65-5-W4M	7	41	3	29	2	2.4	0.5	11	-	51	6	41	3	3	2	3	2	1	0.6	3	2.3				
T23	15-22-64-6-W4M	7	48	3	28	2	2.5	0.2	10	1	50	3	40	4	4	1	3	1	<1	0.2	2	0.7				
T25	4-24-62-6-W4M	7	59	4	17	3	3.7	1.0	10	1	54	1	38	2	3	1	3	1	3	1.0	1	0.2	12	1	0.25	0.05
T27	4-6-64-3-W4M	6	48	2	24	2	3.2	0.2	9	-	61	2	29	1	4	1	3	1	<1	0.3	2	1.0				
T30	13-4-62-3-W4M	10	52	3	26	2	3.3	0.4	8	1	59	2	32	3	4	1	3	1	1	0.3	2	0.8	12	1	0.26	0.05
T32	12-1-64-3-W4M	10	53	1	20	2	3.4	0.2	9	<1	58	3	36	2	2	1	1	1	1	0.7	2	0.8	8	1	0.32	0.06
T33	5-32-65-1-W4M	6	45	3	24	4	2.9	0.5	11	1	56	3	34	2	5	1	2	1	<1	0.2	3	0.3	13	3	0.25	0.02
T34	13-18-63-2-W4M	5	48	<1	26	1	3.5	0.2	10	1	55	1	34	2	4	1	4	1	1	0.1	3	1.0				
T38	4-36-64-7-W4M	10	46	2	28	3	2.4	0.2	11	<1	58	4	33	-	3	1	3	1	1	0.5	2	0.6				
T40	4-29-62-6-W4M	1	58		18		3.4		10		57		37		3		2		0		2					
T41	3-29-58-3-W4M	18	43	2	33	1	2.6	0.2	10	<1	60	4	32	3	3	1	3	1	<1	0.5	2	0.9				
T43	16-26-61-7-W4M	11	53	1	20	1	3.2	0.4	9	1	58	2	33	2	4	1	3	1	1	0.6	2	1.0				
T44	14-24-61-6-W4M	3	46	2	27	4	3.2	0.4	9	2	58	1	35	2	1	2	2	2	2	0.2	1	0.8				
T47	12-36-60-6-W4M	2	40	2	29	6	1.9	0.1	10	<1	52	6	40	4	5	2	1	-	2	0.5	1	0.3				
T52	3-5-60-4-W4M	2	48	3	25	1	2.7	0.3	-		59	2	35	.4	5	2	2	1	1	0.5	2	1.2				
T53	4-21-61-4-W4M	6	54	6	19	6	3.3	0.8	9	1	59	4	34	4	3	1	3	1	<1	0.2	1	0.8				
T58	16-13-63-2-W4M	12	51	2	22	2	3.0	0.3	8	1	59	3	30	3	4	1	3	1	1	0.4	2	0.6	14	1	0.39	0.04
T59	1-21-63-3-W4M	7	48	1	24	1	3.5	0.2	9	<1	58	3	30	4	5	1	4	<1	1	0.4	3	0.5	10	3	0.27	0.1
T71	9-25-59-6-W4M	9	42	2	31	2	2.5	0.2	11	1	58	3	33	2	4	1	3	1	<1	0.2	2	0.8				
T73	9-6-65-7-W4M	10	39	2	33	2	2.3	0.3	10	<1	63	4	29	3	3	1	3	1	<1	0.5	1	0.8				
77SR1	1-28-58-8-W4M	23	34	8	19	3	1.7	0.6	12	2	59	4	32	5	3	1	3	2	1	0.3	2	1.2				
77SR2	14-17-58-7-W4M	6	43	1	17	2	1.6	0.2	10	<1	58	4	38	4	1	1	2	1	2	0.8	1	0.6	6	1	0.37	0.1
		2	32	2	36	4	1.6	0	11	<1	66	2	28	1	4	1	1	1	<1	0.2	1	0.6	8	-	0.17	-
77SR3	16-10-58-10-W4M	10	48	2	15	2	2.4	0.3	11	<1	52	5	42	5	2	1	1	1	1	0.7	1	0.6	6	1	0.46	0.4
77SR7	16-29-59-11-W4M	9	37	3	36	4	1.4	0.1	12	1	54	4	37	3	4	1	3	1	1	0.6	2	0.5				
77SR11	1-8-59-10-W4M	5	46	2	28	1	2.5	0.2	9	<1	68	4	24	4	2	1	1	1	1	0.1	1	0.5				
77SR12	1-15-60-10-W4M	1	55		23		2.4		9		52		42		3		2		0		1					
77SR15	9-15-61-13-W4M	18	36	1	33	2	1.6	0.2	10	1	60	3	32	4	3	1	2	1	1	0.9	2	1.0				
77SR20	1-25-63-11-W4M	10	37	3	35	3	1.1	0.2	10	1	48	2	45	3	1	1	1	1	3	0.8	1	0.7				
77SR21	10-18-63-12-W4M	2	39	<1	30	<1	1.4	0.2	12	-	56	-	37	-	2	-	1	-	1	0.4	1	-				
		6	33	2	34	2	1.2	0.5	12	1	65	3	28	3	4	1	2	<1	1	0.4	1	0.3				
77SR23	11-29-65-10-W4M	2	45	1	26	.4	2.2	0.1	9	0	58	5	34	5	5	1	2	2	1	0	1	-				
77SR24	9-19-65-12-W4M	2	39	3	25	1	1.6	0.4	11	1	61	5	32	6	1	1	3	3	1	0.6	1	0.5				
		7	30	3	33	1	0.8	0.1	13	1	59	4	36	5	2	1	2	1	2	1.0	2	0.4				
77SR27	2-36-67-12-W4M	7	36	3	28	1	2.4	0.4	12	1	65	5	26	5	4	1	2	2	<1	0.3	1	0.5				
77SR28	10-22-69-11-W4M	6	47	2	29	2	2.3	0.4	10	<1	64	2	29	2	2	1	3	1	<1	0.3	1	0.3				
		14	38	3	36	3	1.7	0.2	11	1	61	3	32	4	2	1	3	1	1	0.5	1	0.5				
77SR29	8-2-69-13-W4M	12	39	2	27	4	2.0	0.3	10	1	59	2	32	3	3	1	3	1	1	0.3	1	0.3				
77SR30	14-22-69-12-W4M	5	45	3	20	2	1.8	0.2	10	<1	61	2	33	3	1	1	2	1	1	0.6	2	0.1				
77SR31	2-31-69-13-W4M	4	38	2	29	2	2.5	0.1	9	<1	60	2	33	2	3	<1	3	1	1	0.5	1	0.2				
77SR36	9-24-66-4-W4M	12	45	3	27	3	2.6	0.4	10	<1	61	2	33	2	2	1	1	1	2	0.6	2	0.9	6	2	0.59	0.2
		7	47	2	24	2	1.4	0.1	11	<1	51	4	42	4	1	1	1	1	3	0.7	3	0.6				

Appendix B. (continued)

Table 4. (continued)

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties										1-2 mm sand petrology										Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite / Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
			Very sandy eastern facies																							
			n=329		n=329		n=329		n=329		n=329		n=329		n=329		n=329		n=329		n=329		n=101		n=101	
			N=41		N=41		N=41		N=41		N=41		N=41		N=41		N=41		N=41		N=41		N=11		N=11	
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
			48	**5**	**24**	**5**	**2.8**	**0.5**	**10**	**1**	**58**	**4**	**34**	**4**	**3**	**1**	**2**	**1**	**2**	**0.6**	**1**	**0.8**	**10**	**3**	**0.37**	**0.1**
			Western facies																							
			n=119		n=119		n=119		n=119		n=119		n=119		n=119		n=119		n=119		n=119		n=1		n=1	
			N=11		N=11		N=11		N=11		N=11		N=11		N=11		N=11		N=11		N=11		N=1		N=1	
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
			36	**3**	**31**	**5**	**1.6**	**0.5**	**11**	**1**	**59**	**5**	**33**	**5**	**3**	**1**	**2**	**1**	**1**	**0.4**	**1**	**0.5**	**8**	**-**	**0.17**	**-**

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)

n - total number of test hole samples of the unit

N - number of test holes in which unit is recognized

xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $\sum_{1}^{s} \frac{xi}{s}$

σ - sample standard deviation = $\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $\sum_{1}^{N} \frac{\mu i}{N}$

S.D. - standard deviation of the sample means = $\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$

Appendix B. (continued)

Table 5. Marie Creek Formation: Unit 1

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite / Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
T3	6-36-61-1-W4M	15	34	3	38	2	2.4	0.5	13	1	48	4	32	4	7	2	4	1	<1	0.4	9	2.0				
T5	2-16-59-3-W4M	12	32	2	35	1	2.2	0.6	11	1	64	2	22	3	3	1	9	1	1	0.6	1	0.5	17		0.18	0.14
T6	15-31-62-3-W4M	8	26	4	49	6	1.5	0.3	13	1	64	5	27	4	3	1	4	2	1	0.8	2	0.2	12	2	0.21	0.06
T9	13-10-62-2-W4M	4	32	3	36	3	2.2	0.1	10	1	65	2	26	1	3	1	4	1	1	0.8	2	0.5				
T12	4-4-62-4-W4M	2	27	1	38	1	1.2	-	13	-	60	1	33	1	2	-	4	1	<1	0.2	1	0.5				
T13B	1-30-60-2-W4M	4	27	3	38	-	1.3	0.4	11	<1	63	4	24	4	5	.7	6	<1	1	0.5	2	0.4				
T14	4-17-60-3-W4M	2	21	-	39	-	1.3	0.1	11	<1	59	2	30	3	1	-	8	<1	1	0.3	<1	0.4				
T15	16-20-60-1-W4M	6	34	1	33	1	2.0	0.4	11	1	66	1	24	2	2	1	7	2	<1	-	1	0.6				
T16	4-30-61-1-W4M	2	29	1	36	1	2.0	0.1	13	1	61	1	27	2	3	1	6	1	<1	0.1	2	0.3				
T25	4-24-62-6-W4M	6	36	2	36	3	2.4	0.1	10	<1	62	2	30	2	3	1	4	1	2	0.5	1	0.3	13	1	0.21	0.03
T33	5-32-65-1-W4M	8	37	8	31	6	1.5	0.2	12	1	67	1	28	1	2	1	2	1	1	0.7	1	0.5	8	3	0.41	0.05
T38	4-36-64-7-W4M	3	35	1	38	2	2.2	0.1	12	<1	56	1	33	3	4	1	2	<1	1	0.5	2	0.6				
T41	3-29-58-3-W4M	7	35	1	32	2	2.5	0.3	11	<1	62	4	24	4	2	.5	7	1	<1	0.3	2	1.0				
T43	16-26-61-7-W4M	4	35	2	40	2	2.5	0.3	10	1	62	2	24	4	4	1	8	1	<1	0.4	1	0.4				
T44	14-24-61-6-W4M	8	33	1	39	3	2.5	0.2	10	1	67	2	23	1	3	1	7	2	1	1.3	1	0.2				
		2	42	2	34	1	2.5	0.1	9	-	66	<1	26	1	2	<1	5	<1	<1	0.2	1	0.4				
T45	1-9-60-7-W4M	18	30	5	40	6	2.1	0.5	11	1	65	4	22	3	3	1	8	3	<1	0.3	2	0.8	15	1	0.20	0.03
T47	12-36-60-6-W4M	5	28	3	40	2	1.9	0.1	11	<1	61	3	29	2	3	2	6	2	1	0.7	1	0.6				
T51	1-16-59-7-W4M	8	33	1	38	1	2.3	0.2	10	1	66	3	22	4	3	1	7	2	<1	0.1	1	0.7				
T56	14-6-63-4-W4M	4	37	1	37	1	2.9	0.3	10	1	65	1	26	1	5	1	7	2	<1	0.1	1	1.0				
T59	1-21-63-3-W4M	3	35	6	40	7	2.2	0.6	11	1	57	4	29	5	4	1	6	2	1	0.4	4	0.1				
T69	12-29-63-6-W4M	6	32	1	41	2	2.3	0.3	9	1	62	2	28	2	2	1	6	1	1	0.4	1	0.5				
T73	9-6-65-7-W4M	7	22	2	43	2	1.3	0.2	12	<1	60	2	32	3	4	1	2	1	0	-	2	0.4				
77SR8	11-25-61-11-W4M	18	33	5	32	4	2.1	0.3	10	1	65	4	25	3	2	1	7	2	1	0.6	1	0.4				
77SR9	16-7-60-8-W4M	23	31	2	41	2	2.0	0.2	10		66	3	21	2	3	1	8	2	<1	0.3	1	0.6				
77SR12	1-15-60-10-W4M	10	35	3	40	4	2.6	0.1	10	1	61	3	25	3	2	1	9	2	<1	0.3	1	0.1				
77SR17	15-9-61-8-W4M	2	35	1	43	1	1.8	-	9	<1	61	1	27	2	3	<1	6	3	<1	-	2	0.5				
77SR20	1-25-63-11-W4M	7	23	1	43	5	0.8	0.1	11	2	59	4	32	4	3	1	4	1	2	1.4	1	0.5				
77SR22	3-30-64-13-W4M	8	30	2	39	2	0.9	0.2	13	1	64	3	26	4	4	1	4	1	2	0.9	1	0.5				
77SR24	9-19-65-12-W4M	6	31	3	30	3	1.0	0.2	12	1	59	4	29	2	4	1	4	1	2.0	0.8	2	0.9				
77SR34	16-20-66-5-W4M	9	42	1	34	1	1.9	0.3	12	1	65	3	27	2	2	1	4	1	1	0.7	2	0.9				
			n = 227		n = 227		n = 227		n = 227		n = 227		n = 227		n = 227		n = 227		n = 227		n = 227		n = 54		n = 54	
			N = 30		N = 30		N = 30		N = 30		N = 30		N = 30		N = 30		N = 30		N = 16		N = 30		N = 6		N = 6	
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
			32	5	38	4	2.0	0.6	11	1	62	4	27	3	3	1	6	2	1	0.5	2	1.6	13	3	0.25	0.09

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)

n - total number of test hole samples of the unit

N - number of test holes in which unit is recognized

xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $\sum_{1}^{s} \frac{xi}{s}$

σ - sample standard deviation = $\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $\sum_{1}^{N} \frac{\mu i}{N}$

S.D. - standard deviation of the sample means = $\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$

Appendix B. (continued)

Table 6. Marie Creek Formation: Unit 2

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite/Dolomite	
			µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ	µ	σ
T2	4-15-65-2-W4M	7	44	3	30	4	3.3	0.3	9	1	61	3	21	-	4	1	14	-	1	0.4	2	0.6				
													28	3												
T3	6-36-61-1-W4M	7	46	2	26	3	3.1	0.3	11	1	56	2	21	2	5	1	16	1	1	0.5	1	0.6				
													32	4			4	<1								
T5	2-16-59-3-W4M	14	38	3	28	2	3.0	0.3	9	1	61	2	21	2	4	1	13	3	1	0.3	1	0.5	19	1	0.17	0.04
T6	15-31-62-3-W4M	14	44	2	29	2	2.8	0.4	9	1	61	3	18	3	4	1	15	3	1	0.9	2	1.0	19	<1	0.14	0.04
T7	4-1-64-6-W4M	7	38	1	30	1	2.6	0.2	11	<1	57	3	21	2	4	1	17	2	<1	0.2	1	0.7	18	1	0.16	0.02
T8	11-36-62-2-W4M	2	47	1	26	1	3.3	0.3	9	1	59	1	26	2	4	1	9	1	<1	0.3	1	0				
T9	13-10-62-2-W4M	6	42	3	29	2	3.1	0.4	9	<1	61	3	19	2	3	1	15	1	1	0.5	1	0.5				
													24	5			6	2								
T10	9-16-63-4-W4M	3	37	4	22	3	2.2	0.2	12	1	60	3	25	3	6	1	7	<1	0	-	2	0.4				
T11	9-14-62-5-W4M	7	43	2	27	2	2.8	0.4	10	1	66	4	21	3	3	1	11	1	<1	0.3	1	0.5				
													26	4			5	1								
T12	4-4-62-4-W4M	5	41	3	27	3	3.5	0.4	9	<1	60	3	21	1	5	1	14	1	<1	0.2	1	0.5				
T13	4-27-60-2-W4M	9	38	2	32	1	2.7	0.3	11	1	62	3	19	2	5	2	12	2	1	0.5	1	0.3				
T13B	1-30-60-2-W4M	12	38	1	33	1	2.7	0.2	10	<1	63	3	21	2	4	1	12	2	1	0.5	1	0.5				
													23	3			9	1								
T14	4-17-60-3-W4M	16	39	2	28	3	2.7	0.2	9	1	63	2	19	2	4	1	13	1	1	0.3	2	1.1				
													22	3			9	2								
T15	16-20-60-1-W4M	4	39	1	28	1	2.3	0.3	10	<1	60	.4	17	1	6	2	13	2	1	0.4	3	0.4				
T16	4-30-61-1-W4M	6	45	4	25	3	3.0	0.3	10	1	65	2	21	3	4	1	10	<1	1	0.4	2	1.0				
		4	37	0	32	1	3.0	0.4	11	1	70	2	18	2	4	1	8	1	1	0.4	2	0.6				
T17	7-36-61-3-W4M	19	47	4	29	3	2.7	0.3	9	1	63	4	22	3	3	1	11	3	1	0.4	2	0.6				
													26	4			2	1								
T18	9-18-61-3-W4M	11	42	3	28	4	2.8	0.4	9	1	67	4	16	2	3	2	14	2	<1	0.4	1	0.5				
													21	1			8	1								
T19	16-30-64-2-W4M	18	48	4	25	3	3.3	0.5	10	<1	58	1	22	1	4	1	14	1	1	0.2	2	0.7				
											61	3	28	2	4	1	4	1	1	0.2	2	0.7				
											71	2	24	2	2	1	2	<1	1	0.2	1	0.4				
T20	1-26-64-5-W4M	5	50	2	23	2	2.8	0.2	10	1	60	3	29	2	4	<1	6	1	<1	0.2	2	0.6				
T22	7-19-65-5-W4M	14	53	4	20	4	4.0	1.0	10	1	64	3	28	3	3	1	4	2	<1	0.5	1	0.7				
											53	1	40	4												
T23	15-22-64-6-W4M	6	42	6	28	7	2.4	0.4	12	1	55	2	33	1	4	1	8	1	1	0.3	1	0.4				
													36	2			3	1								
T25	4-24-62-6-W4M	9	41	3	25	3	2.7	0.2	9	1	57	2	24	3	5	1	11	2	1	0.8	0		20	2	0.14	0.02
T27	4-6-64-3-W4M	4	41	2	27	1	2.8	0.3	9	1	65	1	19	-	3	1	13	-	<1	0.3	<1	0.4				
													23	1			8	1								
T29	9-34-63-2-W4M	11	42	3	30	2	2.9	0.2	10	1	59	4	21	2	4	1	15	3	1	0.5	2	1.3				
													27	4			5	1								
		5	!48	1!	24	1	3.6	0.2	10	1	62	2	27	1	5	1	3	<1	1	0.5	2	0.6				
T30	13-4-62-3-W4M	13	42	4	30	4	2.6	0.4	9	1	63	2	22	2	3	1	9	2	1	0.5	1	[illegible]	16	2	0.19	0.01
													34	3			3	2					11	-	0.25	-
T32	12-1-64-3-W4M	5	40	1	31	1	2.4	0.1	9	1	66	2	17	1	4	1	11	2	1	0.6	2	[illegible]	17	1	0.18	[illegible]
													21	2			8	1								
		4	!52	5!	23	3	3.0	0.5	7	1	58	2	32	2	4	1	5	1	1	0.6	2	0.9	12	<1	0.26	0.02
T33	5-32-65-1-W4M	7	42	2	31	2	2.9	0.3	11	1	68	2	21	2	4	1	11	2	1	0.4	1	0.4	16	1	0.17	-
													21	2			7	1					14	2	0.18	0.1
		14	!48	1!	23	5	2.9	0.3	10	1	63	2	27	3	4	1	3	1	1	0.4	2	0.7	12	1	0.30	0.04
T34	13-18-63-2-W4M	8	48	1	27	2	3.6	0.3	10	<1	63	3	26	2	4	1	3	<1	1	0.8	3	1.7				
T36	13-4-63-6-W4M	1	46	-	19	-	2.0	-	11	-	63	-	3	-	26	-			6	-	0	-			0.8	-
T38	4-36-64-7-W4M	9	43	1	28	2	2.7	0.2	11	1	56	3	26	-	4	1	10	-	<1	0.5	2	0.7				
													34	1			5	2								
T41	3-29-58-3-W4M	17	38	2	31	2	2.7	0.3	10	<1	60	2	25	4	3	1	10	1	1	1.5	1	0.7				
T42	13-5-65-3-W4M	10	41	1	31	1	2.8	0.3	9	<1	60	3	23	2	3	1	11	2	1	0.6	1	0.7				
T43	16-26-61-7-W4M	3	39	2	35	2	2.3	0.3	10	1	61	6	22	4	4	2	15	2	<1	0.4	2	1.3				
T44	14-24-61-6-W4M	10	40	1	28	2	2.9	0.3	10	1	62	4	18	2	4	2	15	4	<1	0.3	2	0.8				
T45	1-9-60-7-W4M	5	37	1	30	.4	2.7	0.1	11	<1	59	2	20	1	4	1	14	3	1	0.2	2	0.7	19	1	0.15	0.01
T47	12-36-60-6-W4M	3	35	5	27	6	2.4	0.3	11	1	54	2	23	2	5	2	13	3	1	0.1	1	0.7				

Appendix B. (continued)

Table 6. (continued)

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties				1-2 mm sand petrology						Silt and clay carbonate content	
			Sand %	Clay %	1-2 mm Sand %	Moist. %	Ign. Metm. %	Qtz. %	Lst. %	Dst. %	Qtzite & Qtz.Sst. %	Local %	CO_3 %	Calcite/Dolomite
			μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ
T48	4-28-60-4-W4M	11	37 3	25 3	2.5 0.3	10 1	58 4	23 2	5 2	14 3	<1 0.2	2 1.0	20 1	0.15 0.03
T49	16-12-61-5-W4M	16	42 3	22 3	3.3 0.7	9 1	61 3	19 2	4 1	15 4	<1 0.2	1 0.7		
								25 1		7 1				
T50	16-10-58-5-W4M	23	43 1	31 1	2.5 0.2	10 <1	66 3	26 3	3 1	3 1	3 1.0	1 0.6		
T51	1-16-59-7-W4M	11	36 2	34 1	2.7 0.4	10 <1	66 4	15 3	2 1	12 7	<1 0.1	1 0.8		
								22 3		8 2				
T52	3-5-60-4-W4M	8	40 1	28 1	3.1 0.3	11 <1	56 3	26 2	6 1	9 2	1 0.7	3 1.3		
T54	3-36-63-5-W4M	4	38 3	33 1	2.4 0.2	11 1	56 3	22 2	4 1	17 1	0 -	1 0.3		
T56	14-6-63-4-W4M	7	38 2	27 4	2.6 0.2	8 <1	59 1	20 2	4 1	15 2	<1 0.1	0 -		
		5	!46 3!	24 2	3.1 0.4	9 1	60 1	24 1	4 1	12 2	<1 0.1	0 -		
T58	16-13-63-2-W4M	7	45 1	26 1	3.2 0.3	8 <1	63 1	23 -	4 1	9 -	1 0.5	2 1.0	16 -	0.19 -
								25 2					14 -	0.36 0.03
T59	1-21-63-3-W4M	10	45 3	25 2	3.0 0.5	8 <1	59 4	20 3	4 1	13 1	1 0.4	1 0.8	17 1	0.14 0.01
								28 4					15 2	0.26 0.08
T61	4-29-58-6-W4M	8	38 1	31 1	2.8 0.1	9 <1	58 .2	25 2	4 1	12 1	1 0.4	1 0.6		
T69	11-29-63-6-W4M	7	38 3	28 4	2.8 0.3	9 1	59 2	21 2	4 1	14 1	<1 0.6	1 0.3		
T72	8-1-60-1-W4M	6	39 1	31 1	3.2 0.3	10 <1	63 4	26 2	3 1	9 2	1 0.4	2 0.4		
								33 -		4 2				
T73	9-6-65-7-W4M	6	42 2	22 1	2.8 0.2	10 <1	62 3	24 2	3 1	9 1	<1 0.2	1 0.4		
T74	11-1-63-3-W4M	10	44 1	31 1	2.6 0.2	9 <1	64 3	26 2	3 1	5 1	1 0.4	2 0.7		
77SR7	16-29-59-11-W4M	8	41 2	31 2	2.2 0.2	10 <1	62 2	28 3	2 1	6 1	1 0.4	1 0.5		
77SR8	11-25-61-11-W4M	6	34 4	26 2	2.2 0.3	9 1	52 3	18 3	6 1	19 4	<1 0.2	3 0.4		
77SR9	16-7-60-8-W4M	24	35 1	35 3	2.2 0.1	8 1	68 3	19 2	3 1	9 2	1 0.6	1 0.6		
								19 2		9 2				
77SR17	15-9-61-8-W4M	5	37 2	35 6	2.4 0.1	8 1	62 3	19 3	3 1	14 3	1 0.2	1 0.5		
77SR18	9-2-63-9-W4M	4	39 4	29 4	2.0 0.1	9 1	57 2	25 3	3 1	14 3	<1 0.5	1 0.1		
77SR20	1-25-63-11-W4M	11	35 2	35 3	1.1 0.3	10 1	52 4	33 2	5 2	5 1	3 1.0	2 0.7		
77SR22	3-30-64-13-W4M	7	35 3	33 4	1.0 0.1	12 1	59 3	26 4	6 1	5 1	2 0.9	2 1.0		
77SR23	11-29-65-10-W4M	6	39 2	28 2	2.3 0.2	10 2	66 2	26 4	3 1	6 1	<1 0.3	2 0.6		
77SR24	9-19-65-12-W4M	6	39 1	26 1	1.7 0.5	11 1	65 2	28 2	3 1	4 1	1 1.3	1 0.6		
77SR34	16-20-66-5-W4M	12	49 2	27 2	2.7 0.2	10 <1	62 5	19 -	3 1	11 -	<1 0.4	2 1.0		
								27 4		4 1				
77SR35	2-6-66-4-W4M	9	42 1	30 1	2.9 0.3	10 1	64 3	20 2	3 1	12 3	1 0.5	1 0.8	15 1	0.19 0.05
77SR36	9-24-66-4W4M	17	45 3	28 2	3.1 0.5	10 1	66 3	19 1	4 1	13 3	1 0.5	2 0.7	15 1	0.18 0.05
								22 3		5 1			13 1	0.30 0.05
		6	!50 1!	22 1	3.3 0.2	10 <1	67 2	21 3	4 1	5 1	1 0.6	2 0.6	14 2	0.32 0.09
High dolostone facies (excludes very sandy lower facies)														
			n=535 N=62	n=535 N=62	n=535 N=62	n=535 N=62	n=535 N=62	n=265 N=49	n=535 N=62	n=270 N=49	n=535 N=62	n=535 N=62	n=132 N=14	n=132 N=14
			$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.
			41 4	**29 3**	**2.7 0.5**	**10 1**	**61 4**	**21 3**	**4 2**	**13 2**	**1 0.6**	**2 0.7**	**17 2**	**0.17 0.02**
Low dolostone facies														
								n=277 N=39		n=284 N=39			n=40 N=6	n=40 N=6
								$\overline{X}$ S.D.		$\overline{X}$ S.D.			$\overline{X}$ S.D.	$\overline{X}$ S.D.
								26 2		**6 2**			**13 2**	**0.26 0.06**
! **High dolostone facies** (very sandy lower facies)														
			n=34 N=5	n=34 N=5	n=34 N=5	n=34 N=5	n=34 N=5	n=34 N=5	n=5 N=1	n=5 N=1				
			$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.	$\overline{X}$ S.D.		
			49 2	**23 1**	**3.2 0.3**	**9 1**	**62 3**	**24 -**	**4 -**	**12 2**	**1 0.3**	**2 0.3**		

Appendix B. (continued)

Table 6. (continued)

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties				1-2 mm sand petrology						Silt and clay carbonate content	
			Sand %	Clay %	1-2 mm Sand %	Moist. %	Ign. Metm. %	Qtz. %	Lst. %	Dst. %	Qtzite & Qtz.Sst. %	Local %	CO₃ %	Calcite/Dolomite
			μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ	μ σ
				! Low dolostone facies										
								n = 29 N = 4		n = 29 N = 4		n = 19 N = 3	n = 19 N = 3	
								$\overline{X}$ S.D.		$\overline{X}$ S.D.			$\overline{X}$ S.D.	$\overline{X}$ S.D.
								27 4		4 1			13 1	0.29 0.03

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)
n - total number of test hole samples of the unit
N - number of test holes in which unit is recognized
xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $\sum_{1}^{s} \frac{xi}{s}$

σ - sample standard deviation = $\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $\sum_{1}^{N} \frac{\mu i}{N}$

S.D. - standard deviation of the sample means = $\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$

Appendix B. (continued)

Table 7. Grand Centre Formation: Hilda Lake Member

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology														Silt and clay carbonate content			
			Sand % μ	σ	Clay % μ	σ	1-2 mm Sand % μ	σ	Moist. % μ	σ	Ign. Metm. % μ	σ	Qtz. % μ	σ	Lst. % μ	σ	Dst. % μ	σ	Qtzite & Qtz.Sst. % μ	σ	Local % μ	σ			CO$_3$ % μ	σ	Calcite/Dolomite μ	σ
T2	4-15-65-2-W4M	23	27	1	44	2	0.8	0.2	15	1	66	5	24	3	2	1	2	1	4	2.5	1	0.7						
T6	15-31-62-3-W4M	1	27		39		0.9		12		78		17		2		0		3		0				11		0.26	
T7	4-1-64-6-W4M	11	26	2	35	1	0.8	0.1	13	<1	72	3	24	4	1	1	1	1	1	1.0	<1	0.3			11	1	0.24	0.1
T8	11-36-62-2-W4M	2	31	6	41	6	1.3	0.3	13	1	72	5	20	4	2	.4	3	.2	1	0.8	12	11						
T9	13-10-62-2-W4M	2	27	1	46	1	1.3	0.2	13	1	70	5	18	3	1	1	3	1	1	0.4	2	0.6						
T10	9-16-63-4-W4M	6	25	5	30	3	1.4	0.3	14	2	63	3	26	4	4	1	5	1	<1	0.3	4	0.7						
T11	9-14-62-5-W4M	2	28	1	38	1	0.7	0.2	14	1	74	2	21	1	2	1	2	1	1	0.2	1	0.6						
T12	4-4-62-4-W4M	7	32	2	39	3	0.9	0.2	12	1	71	2	26	3	1	1	1	1	1	0.8	<1	0.5						
T13B	1-30-60-2-W4M	2	26	9	44	6	1.1	0.7	14	-	64	3	21	2	5	2	8	7	<1	0.5	1	0.1						
T18	9-18-61-3-W4M	7	33	1	42	1	1.7	0.2	14	1	73	2	22	2	1	-	2	1	1	0.5	<1	0.5						
T20	1-26-64-5-W4M	3	24	-	52	3	0.9	0.1	14	-	73	-	23	1	2	-	2	-	2	0.6	1	-						
T23	15-22-64-6-W4M	1	27		37		1.0		15	1	66		26		2		1		1		3							
T25	4-24-62-6-W4M	9	29	2	40	2	1.0	0.2	12	1	66	3	26	4	5	4	2	2	1	0.9	<1	0.2			12	2	0.26	0.05
T27	4-6-64-3-W4M	7	28	1	40	1	1.0	0.1	15	-	71	2	23	2	1	1	1	1	2	0.8	1	0.3						
T29	9-34-63-2-W4M	2	17	6	55	2	1.1	0.5	15	3	66	3	26	2	2	1	3	1	1	0.8	2	0.6						
T31	1-2-63-1-W4M	20	26	5	44	5	0.9	0.2	13	2	74	4	22	3	1	1	1	1	1	1.0	4	0.3						
T32	12-1-64-3-W4M	2	23	4	48	2	0.9	0.3	14	-	69	-	21	2	3	1	5	-	0	-	1	0.5			11	1	0.25	0.01
T34	13-18-63-2-W4M	3	32	1	42	2	1.5	0.2	13	1	65	2	26	2	2	-	4	1	1	0.5	1	0.3						
T40	4-49-62-6-W4M	2	26	-	46	2	0.8	-	12	-	70	3	23	5	1	1	3	1	2	-	<1	0.6						
T42	13-5-65-3-W4M	4	26	5	38	9	1.0	0.5	13	1	63	5	27	6	2	1	5	3	3	0.2	<1	0.6						
T44	14-24-61-6-W4M	3	31	2	39	4	0.9	0.3	12	-	65	2	28	3	1	-	2	1	1	0.6	1	1.0						
T45	1-9-60-7-W4M	5	26	3	48	3	0.9	0.3	12	-	72	4	21	3	2	1	1	1	1	0.6	1	0.6			12	1	0.21	0.04
T48	4-28-60-4-W4M	12	24	1	49	2	0.8	0.1	14	1	76	3	20	2	2	1	1	1	1	1.0	<1	0.8			12	1	0.26	0.05
T49	16-12-61-5-W4M	2	27	8	39	5	1.4	0.3	15	2	74	6	18	2	2	1	6	3	0	-	<1	0.3						
T52	3-5-60-4-W4M	1	16		54		0.7		14		-		-		-		-		-	-	-							
T54	3-36-63-5-W4M	23	30	3	40	4	0.9	0.3	14	1	70	6	24	7	2	1	2	1	1	1.0	<1	0.4			11	2	0.34	0.05
T58	16-13-63-2-W4M	6	22	2	46	1	0.9	-	13	1	65	6	24	4	4	2	3	1	1	0.4	3	0.2			11	2	0.34	0.05
T59	1-21-63-3-W4M	5	28	1	33	1	0.9	0.1	11	-	63	2	21	3	3	2	11	4	1	0.7	<1	0.1						
T75	6-26-62-2-W4M		Glacially displaced beds of Marie Creek Fm., Bonnyville Fm., and Lea Park Fm.																									
77SR18	9-2-63-9-W4M	6	31	1	46	4	1.0	0.1	13	-	59	3	29	1	3	1	4	1	2	0.5	2	1.0						
77SR19	9-13-64-9-W4M	5	25	9	53	8	1.1	0.4	9	2	68	2	27	2	1	1	2	1	2	0.9	<1	0.2						
77SR35	2-6-66-4-W4M	2	27	5	44	5	1.1	0.3	15	1	67	2	22	6	2	-	7	4	1	0.8	<1	-			10	-	0:11	0.04
			n=166		n=166		n=166		n=166		n=166		n=166		n=166		n=166		n=166		n=166				n=53		n=53	
			N=30		N=30		N=30		N=30		N=30		N=30		N=30		N=30		N=30		N=30				N=8		N=8	
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.			$\overline{X}$	S.D.	$\overline{X}$	S.D.
			27	**4**	**43**	**6**	**1.0**	**0.2**	**13**	**2**	**69**	**4**	**23**	**3**	**2**	**1**	**3**	**2**	**1**	**0.8**	**2**	**2.2**			**11**	**1**	**0.24**	**0.06**

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)

n - total number of test hole samples of the unit

N - number of test holes in which unit is recognized

xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $\sum_{1}^{s} \frac{xi}{s}$

σ - sample standard deviation = $\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $\sum_{1}^{N} \frac{\mu i}{N}$

S.D. - standard deviation of the sample means = $\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$

Appendix B. (continued)

Table 8. Grand Centre Formation: Reita Lake Member

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite / Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
T3	6-36-61-1-W4M	4	44	5	32	1	2.0	0.6	13	2	65	3	26	2	2	1	4	1	1	0.4	1	0.8				
T5	2-16-59-3-W4M	4	35	1	39	2	1.5	0.4	16	1	70	1	26	4	3	1	3	1	1	0.7	1	0.3	12	1	0.32	0.1
T6	15-31-62-3-W4M	5	35	2	38	1	1.7	0.4	15	-	75	4	20	3	1	1	2	1	1	0.4	1	0.2	10	1	0.30	0.1
T7	4-1-64-6-W4M	26	35	5	36	5	1.5	0.4	13	2	69	4	25	4	2	1	2	1	1	0.8	1	0.9	12	1	0.23	0.04
T10	9-16-63-4-W4M	3	34	2	23	2	1.5	0.1	9	1	72	2	22	2	3	1	3	1	2	0.9	1	0.1				
T11	9-14-62-5-W4M	11	42	4	29	5	1.6	0.4	12	2	70	3	24	2	2	1	2	1	1	0.6	1	0.6				
T12	4-4-62-4-W4M	4	38	2	35	3	1.8	0.2	16	1	67	2	27	3	2	1	2	0	2	0.5	1	0.5				
T13	4-27-60-2-W4M	9	38	2	36	3	1.3	0.3	14	1	73	4	22	3	2	1	4	1	1	0.5	1	0.2				
T14	4-17-60-3-W4M	2	34	2	23	2	1.5	0.1	12	1	72	2	22	2	3	1	3	1	1	0.4	1	0.1				
T15	16-20-60-1-W4M	2	46	2	33	4	1.8	0.3	12	1	74	3	21	1	1	-	5	-	1	-	1	0.1				
T16	4-30-61-1-W4M	2	43	1	30	3	2.0	0.3	9	<1	72	-	21	-	2	-	3	-	1	-	1	-				
T17	7-36-61-3-W4M	5	42	4	33	4	1.8	0.3	12	1	70	3	23	3	2	-	3	1	1	0.5	<1	0.4				
T19	16-30-64-2-W4M	3	38	3	37	4	1.5	0.1	16	2	69	3	26	2	0	-	3	1	1	0.8	1	-				
T22	7-19-65-5-W4M	6	42	2	32	2	1.7	0.2	13	1	70	4	22	3	2	1	4	1	1	1.0	1	0.6				
		12	42	2	32	2	2.9	0.4	10	<1	73	4	20	3	2	1	4	1	1	1.0	1	0.6				
T23	15-22-64-6-W4M	3	41	1	32	1	1.7	0.1	11	1	63	2	30	-	2	-	3	2	1	0.4	1	0.3				
T25	4-24-62-6-W4M	7	40	4	35	2	1.6	0.2	12	2	67	3	29	4	3	1	1	1	3	2.0	<1	0.3	11	2	0.27	0.1
T27	4-6-64-3-W4M	3	36	4	34	1	1.4	0.1	13	1	70	1	26	5	2	1	2	1	2	0.7	1	0.4				
T30	13-4-62-3-W4M	2	37	3	40	0	1.7	0	14	2	72	5	24	-	2	1	2	1	2	1.1	2	-	12		0.36	
T31	1-2-63-1-W4M	15	38	1	35	2	2.0	0.3	13	1	76	4	20	3	1	1	2	2	1	0.4	1	0.5				
T32	12-1-64-3-W4M	7	35	2	39	2	1.8	0.1	14	1	66	2	27	1	2	1	4	1	2	0.9	1	0.5	11	1	0.27	0.06
T33	5-32-65-1-W4M	1	41		42		2.6		13		70		25		1		2		<1		<1					
T35	12-27-63-7-W4M	13	34	2	38	1	1.5	0.2	12	1	66	4	27	4	2	1	3	1	1	0.7	<1	0.4				
T36	13-4-63-6-W4M	10	35	2	37	4	1.5	0.2	12	2	71	5	25	3	1	1	2	1	1	1.0	1	0.9				
T38	4-36-64-7-W4M	3	44	2	32	1	1.9	-	11	1	62	3	27	2	3	-	2	-	3	0.3	5	0.2				
T41	3-29-58-3-W4M	7	35	3	38	4	1.5	0.1	14	1	64	4	28	3	2	1	3	1	<1	0.2	1	0.9				
T42	13-5-65-3-W4M		Mixed tills of the Reita Lake Member and ice-thrust Marie Creek Formation.																							
T44	14-24-61-6-W4M	6	40	3	36	3	1.6	0.2	10	-	71	3	24	3	2	1	2	1	1	1.4	1	0.5				
T45	1-9-60-7-W4M	8	35	3	38	3	1.4	0.3	12	1	69	4	24	3	2	1	2	1	1	0.8	1	0.9	10	1	0.28	0.04
T46	16-23-60-6-W4M	16	37	3	35	4	1.6	0.2	11	1	68	3	27	4	2	3	2	2	2	0.8	1	1.1				
T47	12-36-60-6-W4M	6	36	3	37	2	1.4	0.2	12	1	65	8	28	9	1	1	3	2	2	0.6	1	1.0				
T48	4-28-60-4-W4M	9	36	1	36	2	1.5	0.2	12	1	69	2	26	2	1	1	2	2	1	0.7	<1	0.8	13	2	0.27	0.1
T49	16-12-61-5-W4M	4	39	1	35	1	1.6	0.3	14	1	71	2	22	4	2	1	4	1	1	0.7	<1	0.8	13	2	0.27	0.1
T50	16-10-58-5-W4M	2	44	1	32	2	1.5	0.2	10	1	69	6	25	1	0		2	1	<1	0.3	2	0.4				
T52	3-5-60-4-W4M	3	36	1	38	2	1.6	0.3	12	-	70	3	27	2	2	1	1	1	2	0.4	2	1.1				
T53	4-21-61-4-W4M	32	37	3	34	2	1.6	0.3	11	1	70	4	24	4	1	1	2	1	1	0.5	<1	0.4				
T56	14-6-63-4-W4M	8	37	2	36	2	1.4	0.3	10	1	70	3	25	2	1	1	2	1	1	0.6	1	0.5				
T57	16-8-60-5-W4M		Glacially stacked sequence of clayey tills																							
T58	16-13-63-2-W4M		Glacially displaced beds of Bonnyville Formation till																							
T59	1-21-63-3-W4M	6	34	3	43	5	1.6	0.3	12	1	68	4	23	3	1	1	4	1	1	1.0	1	0.6	9	4	0.30	0.1
T69	12-29-63-6-W4M	16	37	2	35	2	1.6	0.2	10	1	70	4	24	3	2	1	2	1	1	0.7	1	0.6				
T71	9-25-59-6-W4M	3	36	2	38	3	1.5	0.2	16	2	72	3	26	-	4	1	2	1	1	0.3	1	0.5				
T72	8-1-60-1-W4M	6	44	1	32	1	2.2	0.2	11	-	71	2	25	1	1	-	1	1	2	0.6	1	0.3				
T73	9-6-65-7-W4M	3	42	6	33	5	1.5	0.3	9	1	66	9	25	2	7	-	4	-	1	0.5	1	0.3				
77SR17	15-9-61-8-W4M	8	35	3	38	3	1.7	0.3	9	-	68	5	24	3	2	1	4	2	2	0.5	<1	0.1				
77SR18	9-2-63-9-W4M	8	36	4	41	3	1.3	0.2	11	1	66	2	27	3	1	1	3	1	1	0.5	<1	0.5				
77SR19	9-13-64-9-W4M	2	39	-	40	4	2.0	0.4	8	-	53	-	43	-	1	1	0	-	2	1.3	1	0.4				
		2	30	5	48	-	1.4	0.1	12	2	63	8	32	5	1	-	3	1	1	0.4	1	0.6				
		9	36	3	44	2	1.7	0.2	9	1	70	2	27	2	1	-	1	-	1	0.4	1	0.3				
77SR33	4-27-65-7-W4M	39	Ice-thrust Marie Creek Formation																							
77SR34	16-20-66-5-W4M	16	45	4	32	4	2.8	1.1	11	1	71	3	22	3	2	1	3	1	2	0.6	2	1.0				
77SR35	2-6-66-4-W4M	10	40	2	35	2	1.7	0.2	12	1	69	3	27	3	1	1	1	1	2	0.5	<1	0.2	10	1	0.20	0.04
77SR36	9-24-66-4-W4M	7	42	1	33	1	1.6	0.4	13	1	64	4	24	2	3	2	4	2	3	0.8	11	1.0			0.24	.1
			n=350		n=350		n=350		n=350		n=350		n=350		n=350		n=350		n=350		n=350		n=77		n=77	
			N=51		N=51		N=51		N=51		N=51		N=51		N=51		N=51		N=51		N=51		N=11		N=11	

Appendix B. (continued)

Table 8. (continued)

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties										1-2 mm sand petrology										Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		$\frac{\text{Calcite}}{\text{Dolomite}}$	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
			38	4	36	5	1.7	0.3	12	2	69	4	25	4	2	2	3	1	1	0.6	1	0.7	11	1	0.28	0.04

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)

n - total number of test hole samples of the unit

N - number of test holes in which unit is recognized

xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $\sum_{1}^{s} \frac{xi}{s}$

σ - sample standard deviation = $\sqrt{\sum_{1}^{s} \frac{(xi - \mu)^2}{s - 1}}$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $\sum_{1}^{N} \frac{\mu i}{N}$

S.D. - standard deviation of the sample means = $\sqrt{\sum_{1}^{N} \frac{(\mu i - \overline{X})^2}{N - 1}}$

Appendix B. (continued)

Table 9. Grand Centre Formation: Kehiwin Lake Member

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties								1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %		CO_3 %		Calcite / Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
77SR1	1-28-58-8-W4M	8	41	3	18	1	2.1	0.6	11	1	66	2	26	2	3	1	3	1	1	0.4	1	0.5				
77SR2	14-17-58-7-W4M	17	37	2	29	5	1.7	0.2	11	1	60	3	32	3	3	1	2	1	1	0.6	2	0.7	6	1	0.35	0.1
77SR3	16-10-58-10-W4M	22	41	2	20	1	2.3	0.2	11	1	61	3	31	3	3	1	3	1	<1	0.4	2	0.5	10	2	0.29	0.1
77SR4	13-14-58-11-W4M	28	45	1	19	2	2.5	0.2	11	1	66	3	27	3	3	1	3	1	1	0.6	1	0.5				
77SR5	3-26-59-13-W4M	18	47	2	28	2	2.1	0.2	11	1	61	4	31	3	3	1	3	1	<1	0.5	2	1.1				
77SR7	16-29-59-11-W4M	28	48	1	23	2	2.2	0.2	11	1	57	3	35	3	3	1	3	1	1	0.3	1	0.1				
77SR9	16-7-60-8-W4M	7	43	4	18	3	1.1	0.1	8	1	65	4	24	2	4	2	4	1	2	1.2	2	0.6				
77SR10	1-33-58-9-W4M	42	43	4	20	4	2.3	0.6	8	1	65	5	28	4	3	1	3	1	1	0.5	1	0.7				
77SR11	1-8-59-10-W4M	26	44	2	25	2	2.5	0.2	9	1	68	3	24	3	3	1	3	1	<1	0.3	2	0.9				
77SR15	9-15-61-13-W4M	9	43	2	28	1	1.9	0.2	10	1	63	3	30	4	3	1	3	1	1	0.3	1	0.7				
77SR16	9-18-61-9-W4M	34	Interfingering tills of the Vilna and Kehiwin Lake members																							
77SR17	15-9-61-8-W4M	9	42	3	32	3	1.2	0.1	11	1	56	1	25	2	5	2	5	1	4	1.6	1	0.5				
77SR18	9-2-63-9-W4M	3	40	2	31	-	1.7	0.3	10	1	63	2	30	4	2	1	3	1	<1	0.4	1	0.7				
77SR19	9-13-64-9-W4M	13	45	2	34	2	2.4	0.2	8	1	66	3	28	3	2	1	3	1	<1	0.3	1	0.6				
77SR23	11-29-65-10-W4M	7	46	1	25	3	2.3	0.3	10	-	66	2	23	2	4	1	3	1	1	0.1	1	0.4				
	Thrust Marie Creek till	4	21	6	33	4	0.9	0.2	13	1	57	2	28	2	5	1	6	1	<1	-	1	-				
77SR25	6-29-68-9-W4M	30	Greatly differing properties																							
77SR26	2-8-68-10-W4M	24	42	2	25	2	2.3	0.2	12	1	69	3	25	3	2	1	3	1	1	0.5	1	0.7				
			n = 325		n = 325		n = 325		n = 325		= 325		n = 325		n = 325		n = 325		n = 325		n = 325		n = 45		n = 45	
			N = 17		N = 17		N = 17		N = 17		N = 17		N = 17		N = 17		N = 17		N = 16		N = 17		N = 2		N = 2	
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.
			43	3	25	6	2.0	0.5	10	1	62	4	29	4	3	1	3	1	1	1.0	1	0.6	8	3	0.32	0.04

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)

n - total number of test hole samples of the unit

N - number of test holes in which unit is recognized

xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $\sum_{1}^{s} \frac{xi}{s}$

σ - sample standard deviation = $\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $\sum_{1}^{N} \frac{\mu i}{N}$

S.D. - standard deviation of the sample means = $\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$

Appendix B. (continued)

Table 10. Grand Centre Formation: Vilna Member

Test hole	Location LSD-Sec-Tp-R-Mer	s	Grain size properties										1-2 mm sand petrology												Silt and clay carbonate content			
			Sand %		Clay %		1-2 mm Sand %		Moist. %		Ign. Metm. %		Qtz. %		Lst. %		Dst. %		Qtzite & Qtz.Sst. %		Local %				CO_3 %		Calcite/Dolomite	
			μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ			μ	σ	μ	σ
77SR3	16-10-58-10-W4M	5	36	3	25	3	1.5	0.2	14	1	66	2	27	1	2	1	3	1	1	0.5	1	0.4			11	3	0.33	0.1
77SR4	13-14-58-11-W4M	6	34	4	27	3	1.1	-	13	1	71	-	23	2	2	1	3	1	1	0.7	1	0.3						
77SR5	3-26-59-13-W4M	2	38	-	37	-	1.5	-	17	2	61	4	30	5	3	1	2	1	<1	0.4	3	2.0						
77SR6	9-23-58-13-W4M	22	Mixed tills - highly variable properties.																									
77SR7	16-29-59-11-W4M	5	29	2	39	3	1.2	0.1	15	3	65	3	31	3	3	1	2	1	1	1.0	1	0.1						
77SR8	11-25-61-11-W4M	20	33	3	38	3	1.1	0.2	13	1	59	3	31	3	3	2	4	2	1	0.7	1	0.8						
	Ice-thrust Marie	4	32	1	32	4	1.9	0.1	10	1	57	2	27	2	3	1	11	2	1	0.4	2	5.0						
	Creek till	8	28	5	35	3	0.7	0.1	12	1	63	6	28	4	3	1	4	2	1	1.0	1	0.8						
77SR10	1-33-58-9-W4M	11	33	3	33	5	1.4	0.2	11	1	68	2	24	2	3	1	3	1	1	0.4	2	0.6						
77SR12	1-15-60-10-W4M	22	34	2	41	4	1.2	0.1	12	1	58	3	32	2	3	1	3	1	1	0.6	1	0.8						
	Ice-thrust Marie	6	36	2	36	3	2.7	0.1	10	0	64	4	28	4	2	1	5	0	<1	0.1	1	0.4						
	Creek till	8	25	2	51	2	1.6	0.1	12	1	62	3	28	1	3	1	6	-	<1	0.2	2	0.6						
77SR15	9-15-61-13-W4M	9	39	2	30	2	1.6	0.2	11	<1	72	4	23	3	1	1	2	1	1	0.6	1	0.5						
77SR16	9-18-61-9-W4M	2	26	2	38	1	1.0	0.2	12	1	62	1	31	3	2	1	4	1	2	0.6								
77SR20	1-25-63-11-W4M	7	28	3	42	1	0.8	0.1	22	1	55	4	32	3	2	1	3	1	2	0.6	2	1.0						
	Ice-thrust Marie	5	56	8	21	6	1.5	0.4	9	1	54	2	30	4	5	2	6	1	4	2.0	1	0.3						
	Creek till	7	32	2	36	3	1.2	0.2	9	1	64	4	28	3	2	1	3	1	1	0.3	1	0.5						
77SR21	10-18-63-12-W4M	18	33	3	37	3	1.1	0.4	15	1	62	3	29	4	3	1	3	1	2	0.7	2	0.8						
77SR22	3-30-64-13-W4M	2	43	-	27	-	1.6	-	14	1	43	2	25	3	10	1	14	1	6	0.8	1	0.4						
	Ice-thrust Marie Creek till	10	33	2	34	1	1.3	0.2	13	1	64	3	26	2	2	1	4	1	2	1.0	2	0.5						
77SR24	9-19-65-12-W4M	4	28	4	35	2	0.5	0.3	15	2	59	3	32	3	3	2	5	2	2	1.0	1	1.1						
77SR26	2-8-68-10-W4M	1									79	-	18	-	2	-	3	-	<1	-	<1	-						
77SR27	2-36-67-12-W4M	23	25	6	36	4	0.7	0.3	14	2	66	5	23	4	4	2	3	2	2	0.8	2	1.2						
77SR28	10-22-69-11-W4M	9	21	1	48	4	0.8	0.1	8	1	64	4	28	2	3	1	2	1	1	0.7	1	1.0						
77SR29	8-2-69-13-W4M	8	35	2	32	4	1.9	0.4	11	1	69	3	23	2	3	1	2	1	<1	0.1	2	0.8						
77SR31	2-31-69-13-W4M	3	29	-	35	1	1.5	0.1	11	1	61	1	32	1	2	-	3	1	1	0.1	1	0.2						
			n = 176		n = 176		n = 176		n = 176		n = 176		n = 176		n = 176		n = 176		n = 176		n = 176				n = 5		n = 5	
			N = 19		N = 19		N = 19		N = 19		N = 19		N = 19		N = 19		N = 19		N = 19		N = 19				N = 1		N = 1	
			$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.	$\overline{X}$	S.D.			$\overline{X}$	S.D.	$\overline{X}$	S.D.
			32	4	36	6	1.2	0.4	13	<1	64	5	28	4	3	1	3	1	1	0.7	1	0			11	3	0.33	0.1

s - number of test hole samples included in calculation of sample mean (μ) and standard deviation (σ)
n - total number of test hole samples of the unit
N - number of test holes in which unit is recognized
xi - individual values making up the series of data; ranges from first value, i = 1, to last value, i = s.

μ - sample mean = $$\sum_{1}^{s} \frac{xi}{s}$$

σ - sample standard deviation = $$\sqrt{\sum_{1}^{s} \frac{(xi-\mu)^2}{s-1}}$$

$\overline{X}$ - mean of the sample means from all test holes in which unit is recognized = $$\sum_{1}^{N} \frac{\mu i}{N}$$

S.D. - standard deviation of the sample means = $$\sqrt{\sum_{1}^{N} \frac{(\mu i-\overline{X})^2}{N-1}}$$

Appendix C. Clay mineralogy of representative samples from formations containing glacial diamicton (till), Sand River map area

Formation	Test hole	Location LSD-Sec-Tp-R-Mer	Depth (m)	Illite %	Kaolinite %	Smectite %	Chlorite %
Grand Centre Formation							
Vilna Member	77SR8	11-25-61-1-W4M	6	53	19	18	10
			18	53	19	18	10
			22	51	25	16	7
Kehiwin Lake Member	77SR17	15-9-61-8-W4M	4	58	22	15	5
Reita Lake Member	T3	8-36-61-1-W4M	2	56	23	15	6
			6	63	16	15	6
	T6	15-31-62-3-W4M	2.5	60	20	10	10
			5	55	15	20	10
	T14	4-17-60-3-W4M	2	50	25	19	6
	T41	3-29-58-3-W4M	3	55	20	21	5
			6	56	23	16	3
	T44	14-24-61-6-W4M	7	58	19	18	5
			9	50	28	15	8
			10	54	25	17	4
	77SR17	15-9-61-8-W4M	14	57	23	14	6
	77SR36	9-24-66-4-W4M	3	56	26	15	3
			7	53	26	14	7
Hilda Lake Member	T18	9-18-61-3-W4M	3	55	20	20	5
			6	45	10	35	10
	T42	13-5-65-3-W4M	17	51	24	17	7
Marie Creek Formation							
Unit 1	T3	8-36-61-1-W4M	45	40	30	25	5
			46	45	25	24	6
	77SR8	11-25-61-11-W4M	46	55	23	15	7
			55	50	24	19	7
	77SR17	15-9-61-8-W4M	31	53	24	15	7
Marie Creek Formation							
Unit 2	T3	6-36-61-1-W4M	13	58	23	15	4
			17	59	21	16	4
	T6	15-31-62-3-W4M	9	55	20	20	
			12	55	15	20	10
	T14	4-17-60-3-W4M	17	54	24	17	5
			24	54	26	15	7
			31	55	25	13	7
	T18	9-18-61-3-W4M	17	55	25	15	5
			27	50	25	15	10
	T41	3-29-58-3-W4M	8	63	20	13	4
			24	51	27	15	7
	T42	13-5-65-3-W4M	28	56	26	13	5
			37	56	23	13	5
	T44	14-24-61-6-W4M	17	54	25	21	0
			24	56	27	14	3
	77SR8	11-25-61-11-W4M	33	56	19	18	7
	77SR17	15-9-61-8-W4M	26	63	20	13	4
			29	58	23	14	4
			32	53	24	15	7
	77SR36	9-24-66-4-W4M	11	57	26	11	6
			21	49	25	19	6
			32	48	26	22	5
			34	51	21	21	7
Bonnyville Formation							
Unit 2	T6	15-31-62-3-W4M	36	45	25	25	5
			40	40	30	25	5
	T18	9-18-61-3-W4M	34	45	20	25	10
			37	45	25	20	10
	T41	3-29-58-3-W4M	37	46	41	9	5
			46	52	25	17	6
	77SR28	10-22-69-11-W4M	19	56	21	19	3
			29	47	21	25	8
			49	50	22	20	8
	77SR36	9-24-66-4-W4M	46	49	25	22	4

Appendix D. Differences in the composition of the very-coarse-sand fraction with depth

The comparison of the mineralogic or petrologic compositions of till at different sites is a method commonly applied to characterize, differentiate, and correlate tills. Whereas this technique may be appropriate in many places, it has limited application in those areas where the rock types from the source area have either been diluted by locally derived rock types or where glacial processes have preferentially eroded or removed a particular rock or mineral group from the given size fraction that is examined. In either of these examples, negative dependent relationships with the remaining rock types will result.

To determine if the observed differences within a till unit are due to preferential erosion or to differences in source area, it is necessary to first eliminate the effects of either dilution or erosion so that the inherent characteristics of the till can be examined. To do this, the percentage of each rock type must be recalculated, to exclude the rock type or types that are locally derived and therefore not representative of the rock from the glacial source area. This procedure of "normalizing the data" allows a clearer understanding of the behavior of the rock groups in response to the removal or addition of other rock types (Shetsen 1984).

Comparisons of the differences in the composition of the very coarse sand of all till units in the Sand River area show that for each till certain rock types display inverse dependent relationships. That is, an increase in the percentage of one rock type has a corresponding decrease in the percentage of another rock type. For example, till of the Grand Centre Formation is characterized by a greater ratio of igneous and metamorphic rock to carbonate and quartz, compared to that ratio in the till of either the Marie Creek or Bonnyville formations. Another example is the Marie Creek till, which is characterized by a greater ratio of carbonate to quartz, compared to that ratio in the till of either the Grand Centre or Bonnyville formations. Finally, the Bonnyville till is characterized by a greater ratio of quartz to igneous and metamorphic rock, compared to that ratio of the till of either the Grand Centre or Marie Creek formations.

In the specific case of the Marie Creek Formation, the ratio of carbonate to quartz is characteristically very large at the top of the till unit but decreases either gradationally or abruptly with depth (tables 5 and 6). Using percentages, it may appear that quartz is being added preferentially and is diluting the amount of carbonate with depth. However, the total amount of quartz is greater than the amount of carbonate rock in any given sample of the Marie Creek till, and consequently a change in the amount of quartz more strongly affects the percentage of carbonate rock. An apparent decrease in the ratio of carbonate to quartz with depth can result from one of the following: (1) a significant decrease in the amount of carbonate, with the amount of quartz remaining constant (in which case, the percentage of all other rock types should increase, as well as that of quartz); (2) a significant increase in the amount of quartz, with the amount of carbonate remaining constant (in which case the percentage of all other rock types should show a decrease); and (3) a complex relationship in which the amount of carbonate decreases and the amount of quartz increases, the combination of which would result in a lower carbonate to quartz ratio (but the percentage of the remaining rock types would neither increase nor decrease).

To determine the cause of the decrease in the ratio of carbonate to quartz with depth in the Marie Creek till, it is necessary to first normalize the percentage of carbonate rocks with respect to quartz (the percentage of carbonate rocks is recalculated, excluding quartz from the total), and then to normalize the percentage of quartz with respect to carbonate rocks (the percentage of quartz is recalculated excluding carbonate rocks from the total). Normalizing the data serves to eliminate the dependency between carbonate and quartz and allows each to be compared separately to the remaining rock types. The results of the comparison of the normalized values for the Marie Creek Formation (figure 43) indicate that a complex relationship exists; not only does the amount of carbonate in the till decrease with depth (which drives the apparent value of quartz up) but quartz also increases in the till with depth (thereby driving the apparent value of carbonate down).

In some test holes, the decrease in the carbonate-to-quartz ratio is abrupt and not gradational with depth. The abrupt change occurs at the same depth where changes in other properties, such as grain size, also occur. For example, in test hole T15 (Andriashek and Fenton 1979) the amount of quartz in the Marie Creek till increased abruptly at the top of the underlying clayey till of unit 1. Unit 1 is the basal erosional facies of the Marie Creek Formation, as evidenced by the incorporation of silt and clay lenses of the underlying Ethel Lake Formation in the till. It seems probable, therefore, that the increase of quartz and decrease of carbonate near the base of the Marie Creek Formation can be attributed in most places to the erosion and incorporation of the underlying till of the Bonnyville Formation, which has abundant quartz and much less carbonate.

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